DETECTING A VISUAL OBJECT IN THE PRESENCE OF OTHER OBJECTS: THE FLANKER FACILITATION EFFECT IN CONTOUR INTEGRATION

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Detecting a visual object in the presence of other objects: the flanker facilitation effect in contour integration.

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This thesis is submitted in partial fulfilment for the degree of
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at the
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Acknowledgements

The moment I started this Ph.D was the beginning of the most difficult period of my adult life. Yet, there have been some of the most wonderful events of my life during this time too. Although at times I have been doubtful I would manage to recover, never mind getting to this point and completing my thesis, I have managed it in no small part due to the people who have been by my side:

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Abstract

When an observer views a complex visual scene and tries to identify an object, his or her visual system must decide what regions of the visual field correspond to the object of interest and which do not. One aspect of this process involves the grouping of the local contrast information (e.g., orientation, position and frequency) into a smooth contour object. This thesis investigated whether the presence of other flanking objects affected this contour integration of a central target contour.

To test this, a set of Gaborized contour shapes were embedded in a randomised Gabor noise field. The detectability of the contours was altered by adjusting the alignment of the Gabor patches in the contour (orientation jitter) until a participant was unable to distinguish between a field with and without a target shape (2-AFC procedure). By varying the magnitude of this jitter, detection thresholds were determined for target contours under various experimental conditions. These thresholds were used to investigate whether contour integration was sensitive to shared shape information between objects across the visual field.

This thesis determined that the presence of flanking contours of a similar shape (as the target) facilitated the detection of a noisy target contour. The specific results suggest that this facilitation does not involve a simple template matching or shape priming but is associated with integration of shape level information in the detection of the most likely smooth closed contour. The magnitude of this flanker facilitation effect was sensitive to a number of factors (e.g., numerosity, relative position of the flankers, and perimeter complexity/compactness). The implication of these findings is that the processing of highly localised contrast and orientation information originating from a single object is subject to modulation from other sources of shape information across the whole of the visual field.

Chapter 1

Introduction

1.1 Motivation

The detection of an object by the visual system may appear to be a trivial task − a physical object projects an image onto the retina, which sends a signal to the visual cortex of the brain, which in turn processes this image allowing us to 'see' a perceptual object. However, this simple explanation belies the complexity of interpreting the presence of an object from the visual image. For example, the physical object's contour may be obscured by the contour of another physical object, the object may share similar visual features with other objects (e.g., colour, texture), or the physical object may be embedded in a complex background. Therefore, it can be hard to determine which aspects of the visual image should be used in constructing the representation of the perceptual object.

This is a ubiquitous environmental fact that animals with visual systems make use of. A predator, for instance, can use vegetation to hide its presence. The survival of its prey is linked to how well its visual system can distinguish the parts of the visual field belonging to the predator from the ever changing environment it is embedded in. From a psychophysical perspective, studying this process - how an object is seen in the environment - illuminates the conflicting ideas that underlie what is considered 'an object'. For instance, a physical object is commonly understood as any item that exists external to the observer, and has mass and extension and reflects light onto the retina.

However, an observer experiences a perceptual object with specific features (e.g., colour, shape, shading) that are a product of physical properties (e.g., frequency and contrast), contextual factors (what else is present) as well as the intrinsic nature of visual processing. These can be further influenced by factors such as the observer's viewpoint, lighting conditions, memory, expectation or prior exposure. Therefore, a perceptual object has to be considered in terms of both its physical properties, context, as well as the specific constraints of visual processing. For example, the factors that cause the perceptual identification of something as a part of an object (e.g., an arm of a person, the wheel of a car) or a 'whole' object (e.g., A person, A car) have no simple correlation to physical properties objectively described.

This thesis is focused on the appearance of what is traditionally thought of as a whole perceptual object. A perceptual object is defined here as a coherent and segmented region of the visual field that can be perceptually detected and recognised reliably as separate from the surrounding scene.

It was clear from early experimental considerations that object detection is a far more difficult computational problem than it first appears. The initial visual information deriving from an object and its surrounding region is registered in the response of individual cells in the retina. The visual system must then somehow determine which of the very large number of local cell responses distributed over a region of the retina belong to a single, whole perceptual object separated from the rest of the scene (Wallach, 1935). Furthermore, higher level processes related to visual awareness must register the perceptual object before it can be consciously seen. For instance, in a seminal set of experiments (Levin & Simons, 1997; Simons & Chabris, 1999) it was demonstrated that the allocation of attention in the scene could be directed in such a way as to prevent the detection of a prominent object moving through the center of the scene. Detection of objects is therefore not a simple process of passively receiving information, but a complex, dynamic and contextual process involving perceptual and attentional processes that are sensitive to a wide variety of potential sources of disruption and enhancement.

One interesting scientific question that has profound implications for how we understand what we see around us is whether the visual system assumes that every unique bounded image on the retinal projection refers to a unique physical object. Clearly this is not the case (Bedford, 2004) as there are often moments in which distinct projections of objects can be inferred to refer to a single object (e.g., Mirrors, Echoes, Stereoscopy). How then does the visual system determine if two distinct but similar images should refer to the same object (have the same identity) or refer to different objects? When there are numerous similar images, how is individual identity on one hand retained, and how are shared features perceived as such?

Many of these questions are relevant to common perceptual experiences. Examples are everywhere: from being able to identify an individual animal from a herd of other similar animals; recognising a person and their mirror image as being associated; following the complicated shifts in identity in the artistic illustrations of M.C Escher; and in scientific diagrams, such as the meticulously observed drawings documenting the fall of a single mercury droplet (see Figure 1.1) by Arthur Worthington (Worthington, 1894). There are perceptual effects which are perhaps better understood as being a response to a whole set of objects at once.

While it has been long established that localised regions of visual activation can enhance and suppress the activation of adjacent regions and that the presence of multiple higher level features, such as a common semantic meaning, can enhance the speed by which detection occurs (see Section 1.2.5, p.22), a neglected area of research relates to how the presence of a multiplicity of objects affects the perception of a single object itself. Does the presence of a multiplicity of objects aid or impede the perception of an object? Under what conditions does any enhancement or degradation occur? How might the presence of other objects affect the perception of visual details or identity of a single object?

As described previously, the visual system must register and combine a large number of local responses across the visual image as belonging to a single object (Wallach, 1935). In natural scenes this kind of integration of local responses leads to a perceptual representation of the physical object being viewed. This type of integration can also help the visual system 'see' an object that is otherwise obscured in noise. Thus, studying the perception of objects embedded in noise can help us understand how such integrative processes to perceive a single object are affected by the presence of a multitude of other objects. This approach is investigated in the first pilot study.

Such wide-ranging integration of responses also means that the visual system can sometimes construct an illusory, perceptual object based on local information that does not necessarily correspond to a physical object (see Figure 1.2). An example of this is when a set of oriented contour elements form an illusory closed figure or object that perceptually separates from the background (see Figures 1.3 and 1.4). This kind of perceptual creation of an object could also be potentially used to investigate the role of a multiplicity of objects on the perception of a single object. This approach is investigated in the bulk of the experiments reported here.

These experiments use stimuli in which shape information is presented by unconnected local luminance patterns (Gabor patches). These can be spatially organised so as to produce a perceptual object that is an illusory closed contour (Gaborized shape). By altering the difficulty with which such illusory contours are 'seen' or detected the thesis investigates whether their detection is facilitated or suppressed by the presence of a multiplicity of objects. Hence, the experiment seeks to determine whether having multiple separate perceptual objects across the visual field plays a role in the perceptual organisation and detection of a central perceptual object.

The first section of the introduction (p.6) discusses the detection of an object as a perceptual task and how the presence of other objects are known to effect the detection process. An initial pilot experiment, that takes the approach of examining detection of objects embedded in noise is discussed in Chapter 2 (p.30). The chapters (p.51-181) that follow report a series of experiments investigating the effects of the presence of additional objects on the detectability of 2-dimensional objects (shape contours) constructed from Gabor elements. Chapter 7 (p.182) summarises and characterises the results from the 11 experiments.

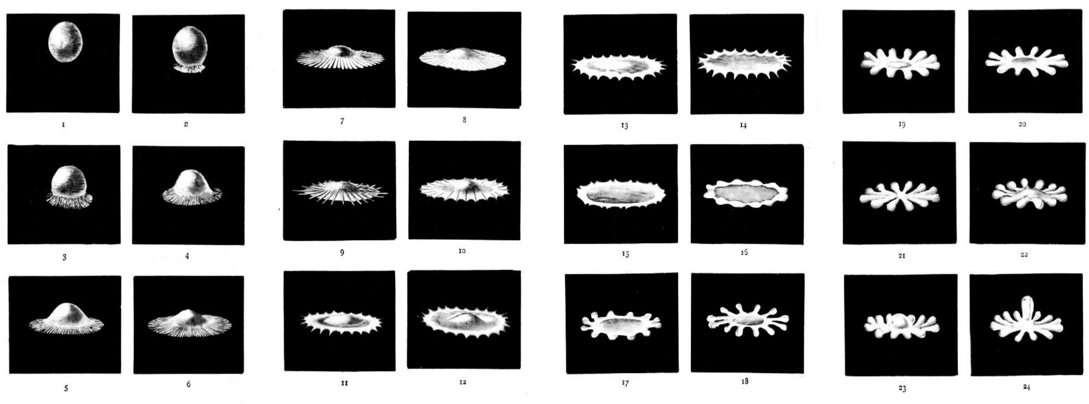

Figure 1.1: **Depictions of Mercury droplets by Arthur Worthington.** Presented here are a series of depictions of a single mercury droplet colliding with a surface. Arthur Worthington created these images by sitting in a darkened room that contained apparatus that dropped mercury at equal time intervals. A flash was used to lighten the room and provide a visual snapshot of the shape of the droplet. The drawings, when presented together, allowed an inspection of the sequential morphology of mercury droplets. Reproduced under free copyright via Project Gutenberg.

1.2 General introduction

1.2.1 Detection of an object - psychophysical sensitivity

The physical world is made up of numerous objects in space that are constantly coming in and out of the view of an observer. What these objects project onto the retina depends on where, when and what the observer is doing. The ability to register an object being present is a fundamental perceptual process that allows an organism to navigate and perform specific tasks such as hunting.

The point at which a visual system can detect the presence of an object is therefore an important methodology for studying how the visual system processes the environment (Swets, 1961). By experimentally constraining and varying the conditions in which an object is detected, important psychophysical factors that degrade or enhance this primary ability of an observer can be determined. Hence, a detection task allows the investigation of what features the visual system is sensitive to, aswell as determine whether these are the results of conscious contingent strategies or represent general perceptual mechanisms.

For the detection process, one of the ways of measuring the performance of the visual system is to identify the smallest possible magnitude of some defined sensory stimulation that can be reliably reported as being present by a participant (Fechner, 1860/1999). This value, known as the detection threshold, can be compared under different stimulus conditions, yielding a measurement of task performance that can be used to determine the factors that influence the behaviour of the visual system. Related metrics, such as the sensitivity index (Tanner & Swets, 1954; Swets, 1985) (e.g., d') can provide additional information regarding the extraction of the signal from the noise in an experiment.

One possible source of information for the visual system to aid in detection and recognition is to identify features in the environment that were unaffected by changes in perspective or projective transformation (Gibson & Gibson, 1957; Gibson, 1979). These invariant features potentially provide a stable and reliable set of ecologically determined features that would be useful to perform detection tasks in most, if not all, environmental circumstances. It was determined that the visual system is indeed sensitive to a number of invariant features such as shape symmetry (Mach, 1885/1959; Attneave, 1954; Delius & Nowak, 1982; Bornstein, Ferdinandsen, & Gross, 1981; Wagemans, 1995; Treder, van der Vloed, & van der Helm, 2011; de Kuijer, Deregowski, & McGeorge, 2004; van der Helm & Leeuwenberg, 1996, 2004; Treder, 2010; Friedenberg, 2000; Baylis & Driver, 2001; Machilsen, Pauwels, & Wagemans, 2009); shape aspect ratio (Zusne & Michels, 1962b; Regan & Hamstra, 1992) and the configuration of an object (the relationship of the parts of an object with respect to the whole) (Rensink, ORegan, & Clark, 1997; Bertamini & Farrant, 2005; Hoffman & Singh, 1997; Keane, Hayward, & Burke, 2003).

An observer can do more than simply detect the presence of an object, they can also

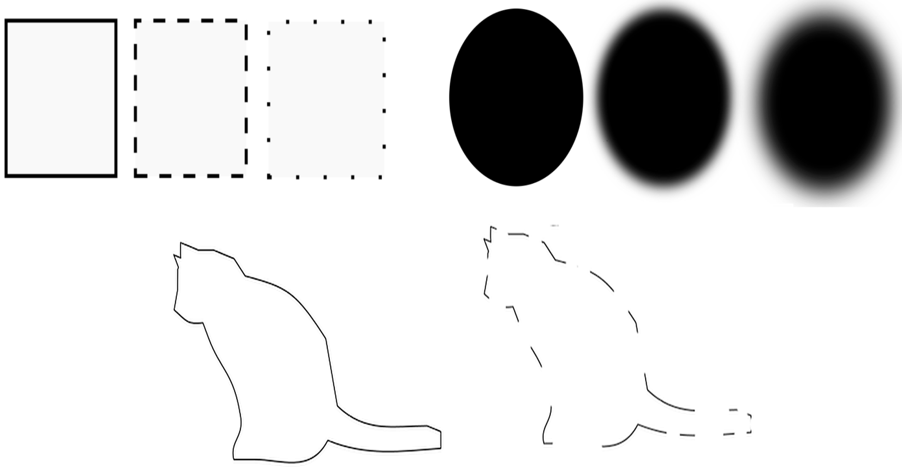

Figure 1.2: **Illusory objects and types of boundaries**
The boundary of an object can be affected by a number of environment factors (e.g., mist, obscuring objects, water distortions in size and shape). In the above diagram a square has been reduced to single points, and a circle has been blurred. Despite this they are still recognisable as geometric shapes. In turn, more complex shapes (In the form of the cat presented above) can still be recognised even though large amounts of continuous information has been lost.

recognise if they have seen the object before and what category the object belongs to (e.g., a mammal, a cat, my cat). These recognition processes can, in turn, influence how the visual system organises and detects objects. In particular, it can affect the determination of the region corresponding to an object or figure and its separation from a background (Peterson & Gibson, 1993, 1994; Peterson, Harvey, & Weidenbacher, 1991). Also, how discrete objects are grouped together (Vickery & Jiang, 2009) has been shown to be modulated by the visual system's ability to recognise and learn new associations. The role of recognition processes will be discussed in greater detail in Section 1.2.2 (p.12) (For a review of quantitative and qualitative approaches to studying visual detection and recognition, see Quinlan, 1991).

One particularly important global shape feature - symmetry - has been shown to be robustly and reliably detected by the visual system (Mach, 1885/1959; Attneave,

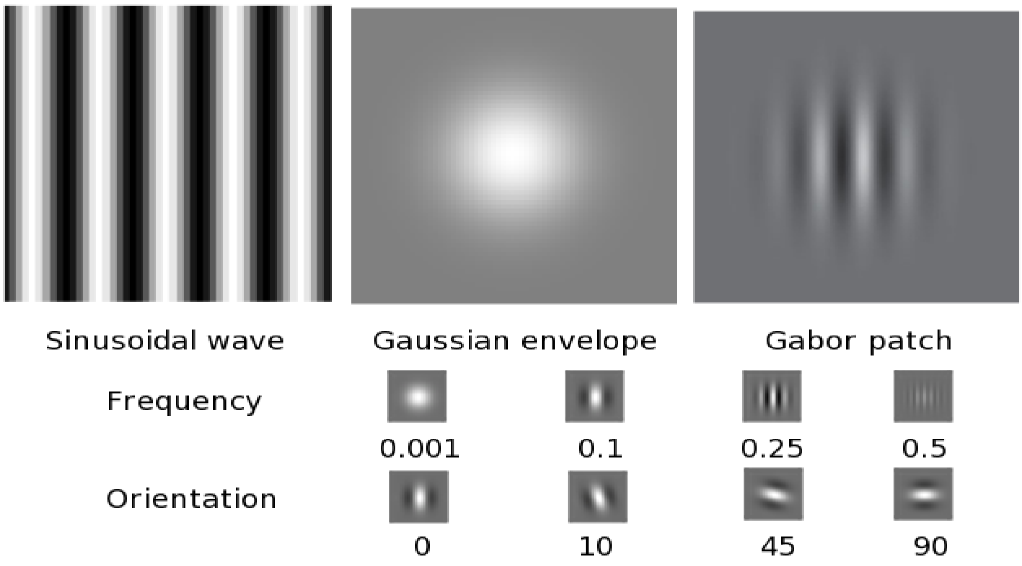

Figure 1.3: **A Gabor patch**

To model the response of cells in the early visual system to the orientation and frequency of luminance a sinusoid is combined with a Gaussian envelope. This produces a Gabor patch. The frequency, contrast, phase and size of these Gabor patches can be adjusted as parameters

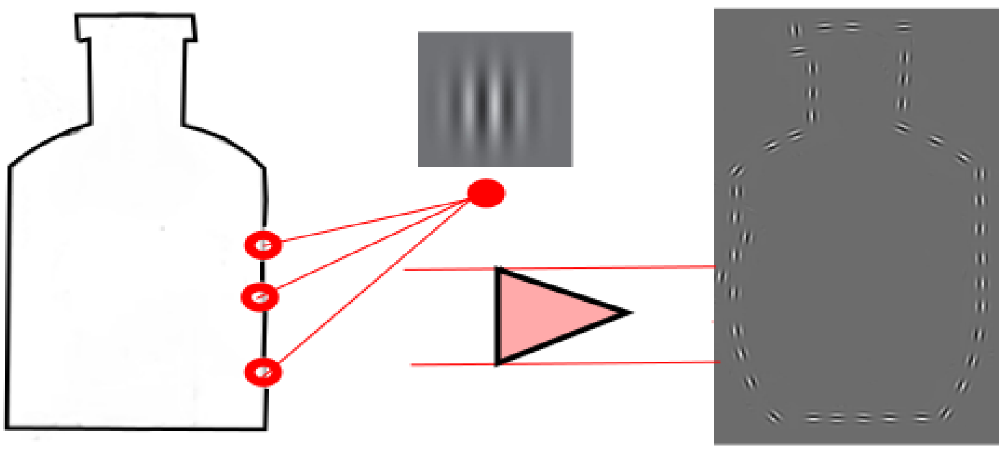

Figure 1.4: **Gaborized contours**

The detection of a shape can occur despite being presented with only broken subsections. To investigate how this contour integration takes place, a model of the neural tuning to the psychophysical parameters of visual contrast (i.e. a Gabor patch) can be used to represent a shape. The resultant Gaborized contour is presented above.

1954; Delius & Nowak, 1982; Bornstein et al., 1981; Wagemans, 1995; Treder et al., 2011; de Kuijer et al., 2004; van der Helm & Leeuwenberg, 1996, 2004; Treder, 2010; Friedenberg, 2000; Baylis & Driver, 2001; Machilsen et al., 2009). Symmetry is mathematically defined as being an invariant in the object to a transformation such as reflection, translation or rotation. Interestingly, symmetries, and in particular bilateral symmetry, are very commonly associated with biological objects and hence the sensitivity to such a feature can be thought of as being ecologically important. For this reason, a large number of studies have focused on bilateral symmetry.

Figure 1.5: **Figure-ground segmentation of one region of the visual field from another**
The luminance information (e.g., the region is black or white) is enough to determine if one region of the visual field is a figure (e.g., the glass or butterfly) or a background. This process is influenced by familiarity and recognition. An example of this is when one region can alternate between figure and background (bi-stability). This leads to the alternating percepts of a candlestick or two faces staring at each other. In the context of the Gaborized contours, the visual field must perform a similar task in which the group of Gabor patches is interpreted as belonging to a figure in some background.

In the context of the present thesis, the most relevant demonstration of the importance of such a feature is that the presence of bilateral symmetry has been shown to contribute to the perceptual organisation of a 2-D contour. In particular, targets that were bilaterally symmetric permitted more efficient grouping of localised regions of contrast than those without. This, in turn, allowed the detection of the resultant contour at ever increasing amounts of noise (Machilsen et al., 2009). This study will be discussed in more detail in the following sections.

To understand how visual features and objects are encoded in the neural architecture of the brain, early research recorded the activity of single neurons when a stimulus was presented to the subject (Hubel & Wiesel, 1959). The responsiveness and activity caused in a neuron by the presence of a psychophysical feature has been shown to be limited to a specific part of the visual field known as the receptive field (Sherrington, 1906; Kuffler, 1953; Hubel & Wiesel, 1962). In the past two decades, the hemodynamic response resulting from the ensemble neural activity in the brain has been used (e.g., fMRI) to further understand visual mechanisms underlying detection and recognition. Using such procedures, a number of observations have been made about the organisation of the visual cortex with respect to visual perception. Using these methods it has been demonstrated that these receptive fields are feature dependent and that the extent of the visual field to which they respond can vary (Kastner et al., 2001).

More specifically, the basic size of the receptive fields for contrast information in the v1 region of the visual cortex has been shown to be <2 deg of the retinotopic field. While, in turn, the receptive fields for shape level information in the v3a and v4 regions have been shown to correspond to a much larger area ($4-6$ deg). The difference between receptive field sizes may indicate that while some processing is local to a specific object, other forms of processing may include visual information deriving from nearby regions and objects. The complex effects in the activity of neurons in the presence of multiple features will be discussed in the final section.

There has been a substantial amount of evidence that suggests that the visual cortex is designed to respond to specific regularities, or features, across the visual field. However, to perform detection the visual system must function in a complicated dynamic environment that involves potential disruptions to such features such as occlusions or distortions. The next section will discuss detection in light of the tasks the visual system needs to perform prior to detection; the role of attention and the dynamic effects on the detectability in the scene will then be discussed (p.17); finally, in the third section (p.22) the importance of the numerosity of objects and features to the visual system will be described in further detail.

1.2.2 Local features and object detection

Though the detection of objects and shapes is often associated with veridical perception (e.g., seeing what is physically there), illusions can occur in which an object is detected that is not present. Many examples of illusory objects and shapes, such as the Kanisza triangle (Kanizsa, 1976) have been demonstrated in which a small number of spatially separate features lead to the seeming presence of a whole shape. Samples of different types of changes in local features that maintain an overall impression of a shape are presented in Figure 1.2.

A number of important observations about the visual system have demonstrated that, while some initial local signal processing occurs in the retina (van Rossum & Smith, 1998; Laughlin, 1994, 1996) the visual cortex must perform computational processes to draw together the correct local features that correspond to a single object (Wertheimer, 1923; Wallach, 1935). Illusions, such as the Kaniza triangle, are indicative and diagnostic of the types of computational process that the neurons in the visual cortex engage in, in order to permit the experience of a perceptual object.

As described in the first section (p.6), the neurons in the v1 region of the visual cortex respond to the highly localised information corresponding to changes in luminance (e.g., contrast, frequency, orientation). It is known that the visual cortex makes use of such local information and systematically organises the responses of the cells.

This process, known as contour integration, induces the appearance of longer coherent contours forming the boundary of an object in a scene (Wertheimer, 1923; Field, Hayes, & Hess, 1993; Gilbert & Wiesel, 1979, 1983; Loffler, 2008). However, the sensitivity to the local features is dependent on their position in the visual field. The sensitivity to contours and their local features decreases with increasing eccentricity from the centre of the fovea region of the eye (Regan & Beverley, 1983). The standard model of how local features are perceptually grouped has been described as an association field (Field et al., 1993) in which the spatial relationships of local features determine the probability of their grouping into a contour. Such effects have been shown to be complex with both spatially dependent enhancement and suppression to the detectability of local features in the presence of flankers (Polat & Sagi, 1993; Adini, Sagi, & Tsodyks, 1997; Zenger & Sagi, 1996; Bonneh & Sagi, 1999; Churan, Richard, & Pack, 2009; Cass & Spehar, 2005; Chen & Tyler, 2001; Freeman, Sagi, & Driver, 2001; Huang & Hess, 2007; Mizobe, Polat, Pettet, & Kasamatsu, 2001; Katkov & Sagi, 2010; Polat & Tyler, 1999; Sterkin, Yehezkel, Bonneh, Norcia, & Polat, 2008; Woods, Nugent, & Peli, 2002).

The importance of such contour integration processes has been underlined by observations made of the neurophysiological responses in regions beyond V1. Activity in these regions occurs in the presence of spatially distributed contour level properties, in particular, curvature has been shown to be important to the v2 region onwards (Blakemore & Over, 1974; Watt & Andrews, 1982; Hoffman & Richards, 1984). On an object and shape level, the presence of more global and holistic features such as whether a contour forms a closed boundary or open loop suggests that specific perceptual mechanisms are present that detect the closure of contours (Elder & Zucker, 1993; Kovacs & Julesz, 1993; Gerhardstein, Tse, Dickerson, Hipp, & Moser, 2012).

The standard perceptual experiment devised to probe how the visual system performs these processes makes use of a model of how neurons respond to local features in the v1 (e.g., contrast, frequency, and orientation. These are shown in Figure 1.3) The response is described by oriented sine wave constrained by a Gaussian envelope, which is known as a Gabor Patch (Marcelja, 1980).

By arranging such Gabor patches spatially, objects can be represented as profiles or Gaborized contours (see Figure 1.4). To investigate the factors that permit the detection of the resultant Gaborized contours the local Gabor patches are then adjusted by changing contrast, orientation or frequency. In doing so it is then possible to identify the psychophysical determinants that enhance or disrupt the contour integration process. However, while this standard procedure investigates the hierarchical processing that link 1st and 2nd order properties (e.g., local orientations and curvature respectively) a number of recent experiments have shown that shape level features play an active role in contour integration. One such feature, the presence of symmetry (see also Section 1, p.6), has been shown to be an important factor for perceptual organisation of a Gaborized contour (Machilsen et al., 2009).

Machilsen et al (2009) studied whether the presence of bilateral symmetry in a contour could affect the detectability of a contour. Using a standard experimental task (2-AFC procedure) they presented two potential stimuli: A field of distracter Gabor patches containing a target Gaborized contour and a second field of distracter Gabor patches containing no target contour. Successively greater degrees of random orientation noise were added to the individual Gabor patches that made up the Gaborized contour until an observer was no longer capable of detecting a contour. The ability to detect the contour despite higher levels of orientation noise was therefore used as a measure of contour integration sensitivity. By comparing examples of shape with or without bilateral symmetry, the authors showed that the detectability of contours was better when symmetry was present in the contour as a global feature, indicating that shapes are more sensitively detected when they contain bilateral symmetry.

Most recently, a set of experiments performed after the completion of the data collection for the current thesis, further examined this effect. Sassi, Demeyer and Wagemans (2014) used eye tracking to determine whether Gaborized contours in the unattended peripheral visual region could be detected when vertical reflective symmetry was present. However, unlike the original study, no contribution of bilateral symmetry could be observed. This study will be discussed further in Chapter 3 (p.51).

In another study published after the data collection in this thesis, Sassi, Demeyer, Machilsen, Putzeys and Wagemans (2014) demonstrated that both predictability, in which participants were presented either a block of trials consisting of either a single target contour (predictable) or multiple interleaved target contours (unpredictable) and familiarity, in which observers were trained with a specific contour shape, facilitated the contour integration process. In a set of older relevant studies (Nygard, Sassi, & Wagemans, 2011; Sassi, Machilsen, & Wagemans, 2012) it was shown that the more readily identifiable an individual contour was, the more detectable a Gaborized contour became.

The effects of familiarity on the perceptual grouping of local features impact on the on-going debate concerning the relationship between a person's ability to determine if an object is present (the object is segmented from a scene) and what that object is (a cat is present in the scene). The complementary processes have been considered to be a two stage hierarchical process in which segmentation occurs prior to any recognition (Nakayama, He, & Shimojo, 1995; Mack, Gauthier, Sadr, & Palmeri, 2008). However, evidence has accrued in which the very fact that the object has an associated identity can influence the segmentation of an object from the scene (Figure/Ground segmentation shown in Figure 1.5) (Peterson et al., 1991; Peterson & Gibson, 1993, 1994). This may indicate that a single perceptual mechanism performs both detection and recognition (Grill-Spector & Kanwisher, 2005).

In the context of both contour integration, and the more general effect of recognition on segmentation, the detection process has been shown to be sensitive to shape level information in the target object. In turn, it has been traditionally assumed that object level detection and recognition (as opposed to local interactions between orientation and contrast) are localised to constrained regions of the visual field, though, performance in both can be enhanced in the presence of other objects or shape level features.

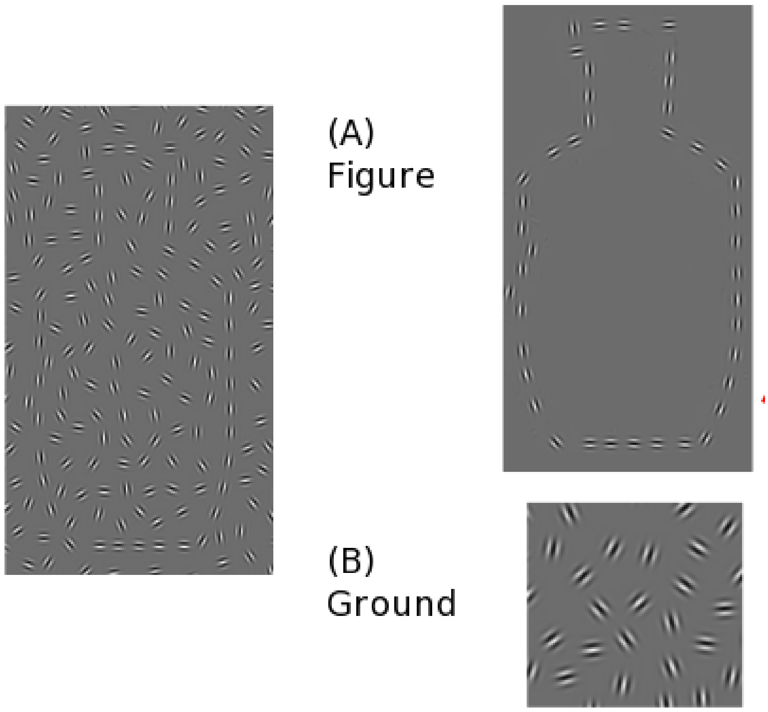

Figure 1.6: **The segmentation of a Gaborized contour from a background of Gabor patches**
In the context of the Gaborized contours, the visual field must interpret the group of Gabor patches as belonging to a figure in some background. The ability to detect a contour is therefore a perceptual process that does not simply group the Gabor patches, but also separates the resultant contour from the background that surrounds it.

The main set of experiments described here (Chapters 3 − 6, p.51 - 181) uses a similar procedure to the investigations by Wagemans and collaborators that have been used to identify a role for bilateral symmetry in the perceptual organisation of local arrangements (2-AFC, detection threshold formulated from the addition of orientation noise). The purpose of using such a methodology here is that contour integration experiments make use of the fact that the visual system can infer a smooth shape from spatially separated local regions of contrast. More simply, an observer sees an illusion of an outline of a cat, despite no continuous contrast information linking all regions and visual details of the overall shape (see Figure 1.2).

The standard method of investigating the psychophysical factors that are responsible for this apparent grouping of lines into an overall contour, is to use local carriers of information (e.g., Gabor patches) and adjust the individual parameters across the whole set of these local carriers (frequency, size, contrast). Spatial arrangements of these Gabor patches so that their orientation aligns with an outline shape (contour) create what is known as a Gaborized contour. By embedding Gaborized contours in a larger field of randomised Gabor patches (shown in Figure 1.6) and adjusting the relative alignment of the shape-associated Gabor patches it becomes possible to make the detection of the contour a function of the ability of the visual system to perceptually group the localised contrast information together into a coherent contour.

The ability to detect an increasingly noisy Gaborized contour within a field of Gabor patches has been shown to be influenced by contextual factors (e.g., presence of bilateral symmetry, familiarity, expectation). However, the detection and relevance of these cues can be dependent on the allocation and direction of attention. The importance of attention and its role in detection will be discussed in the next section.

1.2.3 Attention and the detectability of objects and features.

The ability to detect objects in the visual field occurs in a dynamic environment where the observer is subject to the biological necessities of mating and finding food/shelter, while at the same time avoiding predators and negative environmental conditions. Hence it is not simply enough to detect the goal object, but also to detect specific objects or features relevant to the task at hand given the specific context. One way that biology has accommodated for this necessity is to permit the visual system to focus and attend to specific objects of interest while also distributing attention more broadly (For a review see Evans et al 2011). The complexity of both biological and social demands is reflected in how attentional mechanisms are structured. For instance, attentional processes can be defined by whether a stimulus is selectively chosen by directing the eyes to the location of the stimulus ('overt attention') or, alternatively, by allocating cognitive resources on a stimulus that is not in the direct line of gaze ('covert attention') (Posner, Snyder, & Davidson, 1980).

The study of the attentional factors that effect an observer's ability to detect objects has employed a number of different methodological strategies, these have included: tracking eye movements (Yarbus, 1961, 1967); The study of the attentional factors that effect an observer's ability to detect objects has employed a number of different methodological strategies, these have included: tracking eye movements (Posner, Nissen, & Ogden, 1975; Posner et al., 1980); and presenting a target amongst a number of distracters and determining how efficiently an observer can perform a visual search for the target (Treisman, 1982, 1988, 1991; Treisman & Gelade, 1980). While attention is often conflated with the conscious direction of eye movements, or line of gaze, to a target object, it is known that attention is a more complex process that, in part, automatically responds to the presence of salient cues (Posner et al., 1980). Furthermore, it is known that multiple sub-regions of the visual field can be attended to in a single instance (McMains & Somers, 2004) and that the presentation of high level semantic information primes the attentional system to detect the visual targets with decreased response times and increased accuracy (Maxfield, 1997).

To detect a specific object the visual system has to cope with a large number of task-based demands. To take the example of a hunter searching for a boar, the visual system could selectively attend to different categories of relevant features or items associated with a boar. The hunter could attend to certain regions along the ground within the overall scene where the boar is expected to exist ('location-based'); the hunter could attend to certain types of plants that the boar may seek to eat ('context or object-based'); or the hunter could look out for motion or a specific diagnostic color or material (brown fur), i.e., individual features associated with the boar ('feature-based'). Hence, attention can be defined as a visual mechanism which permits the limited selection of some item(s) according to the type of task-based constraints (Location/Object/Feature) (Carrasco, 2011). Based on this understanding, attentional research has often focused on a specific factor such as the detection and identification of specific features (Driver & Baylis, 1989; Baylis & Driver, 1992; Duncan & NimmoSmith, 1996; Rossi & Paradiso, 1995) or objects (Duncan, 1984; Martinez, Ramanathan, Foxe, Javitt, & Hillyard, 2007).

In turn, however, attention has been demonstrated to be an extremely complex subsystem that operates at the level of both objects and features presented in space (Kravitz & Behrmann, 2011; Simons & Chabris, 1999). One such dramatic example of an interaction between objects in a scene and the allocation of attention was developed by Simons and Chabris (1999). They demonstrated that something as significant as a man walking in a gorilla costume could be impaired when participants were directing their attention to other elements of a scene in which a group of men were passing a basketball between each other.

1.2.4 The detection of Gaborized contours outside of the focus of attention

An alternative approach to attention was developed that investigated what visual information outside of the immediate focus of attention affected the judgements of an observer. The method to do so involved the performance of two perceptual tasks simultaneously: a primary task that the observer must be solely attending to and successfully complete, and a second peripheral task that was outside of immediate, direct attention. This technique is known as a dual-task procedure (Pashler, 1994). The data from the second unattended trial is only accepted if the observer is capable of successfully performing the first. Using this paradigm, it was possible to determine what kinds of visual information is or is not available to the visual system when not directly attending to a target.

Using this technique it has been shown that feature-based attention influences the detectability of object contours created from Gabor patches (Stojanoski & Niemeier, 2007). Their studies investigated the ability of an observer to detect a peripheral unattended contour when it shared a feature in common with a central attended target contour (the features in question were either a contour shape, or motion cue). By adding orientation noise to the alignment of subsequent Gabor patches along the contour they reduced the likelihood that the visual system could perform contour integration on the presented contours. Using a dual-task procedure that extracted psychometric functions measuring the likelihood that a contour in the periphery was detected given a decreasing amount of collinearity.

A secondary, but equally important factor that was identified during this experiment was that the difficulty of the task was instrumental in whether the facilitatory effect was observed. Stojanoski and Niemeier created an easy and difficult task for the performance of the secondary detection task. In these, the participant was required to achieve a detection threshold of either 75 or 95 percent correct responses for the unattended contour. With respect to the contour-based feature, the collinearity of the targets was lower in the more difficult task than in the easier one.

The observers were able to more readily detect the presence of the second, unattended contour when it contained a feature in common with the initial first attended target. In other words, if there was closed shape common to both contours the observer was more readily able to determine the presence of a contour peripheral to the spotlight of attention implying that feature based attention extends beyond the area of the visual field that the visual system is directly accessing. Interestingly, this effect was only observed when the task was the more difficult condition, suggesting that the mechanism is available only when the visual system needs to resolve ambiguity in the task it is performing. In doing so, it showed that the presence of multiple shared features across two contours facilitated the detectability and the contour integration process that underpinned their detection.

These experiments were primarily focused on the role of feature based attention and the modulation of the detection of a contour outside the region of attention and it is not yet clear whether this process is an asymmetric effect. For instance, it has been shown that the attended contours affect unattended contours. However it may be that this is a two way interaction in which peripheral unattended features enhance the detection of the contour in a directly attended region. In this light, the present thesis investigates a potentially complementary effect - does the presence of unattended or less attended object level information modulate the perceptual organisation of a directly attended object?

There are a number of important differences in the approach taken by this thesis and that of the above experiment.

Firstly, familiarity is encoded into the contours by the choice of common everyday objects (e.g., Cat/Butterfly), whereas in comparison, the previous experiment used simple circular loops.

Secondly, the emphasis of the current experiments is on both common shape and the presence of discrete features (e.g., symmetry).

Thirdly, the detection threshold is uniform for all shapes of varying complexity (controlling for this factor is discussed in Chapter 4, p.94).

Overall, the focus of this thesis is to determine whether a single shape found in multiple locations across the visual field affects the detectability of a central contour requiring perceptual grouping. However, when similar objects are present in one region of the visual field it introduces a large number of potential confounds in which commonalities in colour, shape or even symmetry arise. Previous research has demonstrated that there are a number of enhancements to the performance of detection tasks that arise when there is a numerosity of objects. These will be discussed in more detail in the next section.

1.2.5 Object, signal and feature numerosity

The importance of multiple objects in the visual field is a complex and interdisciplinary issue that incorporates many aspects described in the previous sections. For instance, contour integration can be considered a response to the numerosity of local features, while attention can be considered to be an ecological strategy to function adaptively in the context of many objects.

The next three subsections are concerned with the importance of multiple objects and features to the visual system and will demonstrate that the numerosity of objects in the visual field is not accidental to the functioning of the visual system, but is a key component of visual processes and needs to be investigated to develop a fuller understanding of the underlying behaviour that leads to our experience of the world.

Redundancy gain from multiple visual features

The detection of an otherwise un-obscured object by a visual system should seem like a rather trivial process unlike the detection of illusory objects. However, early work on inter-sensory effects by Todd (1912) showed that the speed by which a detection task is performed by an observer could be modulated by the simultaneous presentation of two otherwise separate 'signals' (e.g., an auditory tone and a light). More specifically, the mean response time of an observer to a target was lower when both the tone and light were presented in comparison to the presentation of either the tone or light alone.

In the visual modality, a similar effect has been observed between single feature dimensions of a singleton target being searched for by an observer. In such visual search tasks observers are presented with a large number of possible objects, with the specific target differing from the distracters by being orientated; coloured or orientated and coloured. As with the inter-modal effects, additional features related to the central target detection decreased the mean response time for such targets (Miller, 1982; Toellner, Zehetleitner, Krummenacher, & Mueller, 2011; Krummenacher, Muller, & Heller, 2001, 2002a, 2002b; Ivanov & Werner, 2009; Grubert, Krummenacher, & Eimer, 2011).

The redundancy gain provided by the simultaneous presentation of other relevant features has been shown to be sensitive to the presence of higher-level semantic associations. For instance, an individual letter in the modern Latin alphabet has an upper case and lower case letter for a single phoneme. Ben-David and Algom (2009) presented a target letter (say, the letter 'a') with adjacent flanking letters that had identical visual features ('a'); were related by sharing a semantic role ('A') or varying in shape and semantic meaning ('b' and 'B'). By measuring the mean reaction time corresponding to successful and accurate detection they determined that the presence of both identical visual features and higher-level semantic meaning decreased the mean reaction time.

By using measurements of how quickly target detection occurs, the redundant signals effect is used to investigate how additional information from the various sensory modalities is combined in the act of detecting a target. At a very basic level then, any experiment that presents multiple simultaneous cues may be invoking the temporal benefits in combining two or more signals together.

The present thesis presents multiple 'signals' (objects or contours) to determine whether they play a role in perceptual organisation. Hence, the focus of the thesis differs from redundancy investigations in that it attempts to determine the benefits or detriments to spatial processes (e.g., integration of a contour across the visual field) rather than the temporal benefits of numerosity to detection (e.g., The latency of detection processes). However, it is clear that these two aspects - the temporal and spatial impact of multiplicity - are likely complementary and worthy of future joint investigation.

Encoding of sets of objects

The quantification of objects is often associated with a single value such as the specific orientation of an object with respect to some axis. However, as is used so frequently in science, valuable information can be encoded by taking the average value of group of objects. Humans are remarkably adept at making guesses and judgements about general features in the world (e.g., clouds are white) but less adept at deciphering the specific features (e.g., the complex and sometimes subtle patterns of graduation of luminance and colour in clouds.)

Alvarez (2011) investigated the capacity of observers to make judgements about the general and specific features of sets of objects. Judgements concerning the general features of sets of objects were significantly accurate when compared with the true mean of the set. However, unlike the largely accurate judgements of the mean of some feature, observers were less capable of accurately accessing the individual features involved. This process of encoding the mean values of a feature of a set of objects, or ensemble encoding, was demonstrated to occur for a variety of features such as size (Ariely, 2001; Chong & Treisman, 2003), orientation (Dakin & Watt, 1997; Chong & Treisman, 2003; Parkes, Lund, Angelucci, Solomon, & Morgan, 2001) and the position (Alvarez & Oliva, 2008).

Though primarily focused on cognitive judgements about visual features these behavioural experiments demonstrate that general information derived from sets of objects are available in the visual system. Hence, the human visual system is in some sense functionally designed to process the general information from a scene that may pertain to a group of objects, but may not be necessarily tuned to highly specific information.

Facilitation, Surround suppression and crowding in local features

As has been described in the previous sections, often the neurons in some region of the visual cortex are tuned to specific features and have specific receptive field sizes (see Sections 1.2.1, p.6). However, as with any general process that responds across a specific region, environmental circumstances may lead to congruent and conflicting features lying in a single visual field.

As described in Section 1.2.1, enhancements to the detectability of a localised target feature have been observed when presented in the presence of additional flankers (Polat & Sagi, 1993; Adini et al., 1997; Zenger & Sagi, 1996; Bonneh & Sagi, 1999; Churan et al., 2009; Cass & Spehar, 2005; Chen & Tyler, 2001; Freeman et al., 2001; Huang & Hess, 2007; Mizobe et al., 2001; Katkov & Sagi, 2010; Polat & Tyler, 1999; Sterkin et al., 2008; Woods et al., 2002). Likewise, a single increased size of local feature, or multiple features in close proximity have been shown to have the opposite, suppressive effect in which the central target region becomes less detectable when the adjacent regions are simultaneously occupied by some competing flanking stimuli. This effect is known as psychophysical surround suppression (Tadin, Lappin, Gilroy, & Blake, 2003; Born, 2000; Pack, Hunter, & Born, 2005; Churan et al., 2009; Spillmann, 1994; Troncoso et al., 2007; Petrov, Popple, & McKee, 2007). Other effects can inhibit the recognition of features, in what is described as crowding effects (Bouma, 1970; Stuart & Burian, 1962; Pelli & Tillman, 2008; Toet & Levi, 1992; Levi, 2008; Levi, Hariharan, & Klein, 2002; Parkes et al., 2001; Pelli, Palomares, & Majaj, 2004). Under such conditions the capacity to distinguish the orientation or configuration of a target is affected by the presentation of conflicting flanker information.

The underlying activity of neurons in the visual cortex under such conditions has been well documented in a large number of studies (Kastner, De Weerd, Desimone, & Ungerleider, 1998; Kastner et al., 2001; Desimone & Duncan, 1995; D. M. Beck & Kastner, 2009; Joo, Boynton, & Murray, 2012). Desimone and Duncan (1995) posited that the suppressive effect on activity is due to features competing for the neurons response. However, most recently, the process of presenting redundant information in the presence of a central contrast detection task actively facilitates and increases the activity of certain regions of the visual cortex (Shim, Jiang, & Kanwisher, 2013). This 'redundancy signal gain' may indicate that the most recent understanding of the role of suppression and inhibition of multiple objects and features activating individual or groups of neurons in the visual system may be more complex than previous research has indicated.

Summary of neurophysiological of early visual system

As has been described elsewhere in the introduction (p.3) , one significant task that the visual cortex needs to perform is to integrate the local luminance changes across the retina into a coherent whole object (Wertheimer, 1923; Wallach, 1935; van Rossum & Smith, 1998; Laughlin, 1994, 1996). However, even at this stage of processing the response to luminance on the retina is spatially dependent (Regan & Beverley, 1983), for example, the sensitivity to luminance contrast can vary with eccentricity from the foveal region of the eye.

This disparate information is then passed onto the primary visual system (V1 area). Here, neurons are tuned to specific features (e.g., contrast, frequency, orientation) within a given topographic region of the retina (Wertheimer, 1923; Gilbert & Wiesel, 1979, 1983; Marcelja, 1980). When the spatial distribution of such local features is taken into account, more complex visual features - such as curvature - are formed, and these are represented in regions beyond V1. Changes in curvature, for example, have been shown to trigger neuronal responses in the v2 region of the cortex (Blakemore & Over, 1974; Watt & Andrews, 1982; Hoffman & Richards, 1984). Neurons further in the processing hierarchy are shown to be sensitive to even more global properties such as shape circularity. Sensitivity to circularity is associated with the v4 area of visual cortex (Gallant, Braun, & Vanessen, 1993; Gallant, Connor, Rakshit, Lewis, & VanEssen, 1996; Wilkinson et al., 2000; Wilson & Wilkinson, 1998; Dumoulin & Hess, 2007).

1.2.6 Summary

The numerosity of objects, in its most comprehensive sense, is the duplication of psychophysically relevant but otherwise separable stimuli across the visual field. The underlying neurophysiology of the visual cortex is not thought of as being tuned to a continuous spatial scale, but it is instead linked to specific features and the area of the visual field the feature occupies. This complex system of feature-dependent, spatially linked responses leads to what could be described as feedback and lateral interactions.

The observed behavioural performance is then better considered a function of the context of a whole scene and all the objects present rather than a simple feed-forward detection of whatever is in a single location. For such a system, one plausible intuition is that having shared features for spatially independent objects across a scene could provide additional spatial and organisational information (in the form of feedback) to use for ambiguous 'signals', i.e. those that have a number of different interpretations.

The present thesis investigates this intuition in greater detail in light of the ever increasing amount of research that have demonstrated, not simply top-down effects of cognitive understanding, but also purely perceptual feedback effects on the formation of a percept.

1.3 Experiment overview

This thesis specifically focuses on how the perceptual organisation of objects is affected by the presence of multiple objects, and aims to identify the circumstances in which the detection of an object should be considered more correctly as a function of the whole visual scene. To investigate this a basic experimental paradigm will be used, where the detectability of a target shape is compared in the presence or absence of similar or dissimilar shapes surrounding or flanking the target.

1.3.1 Experiments

Chapter 2 – Is the detectability of a 3-D object embedded in multi-scale noise affected by the presence of neighbouring objects? (Pilot experiment)

The initial pilot experiment developed a methodology to investigate the effects of object-level configural information on low-level features. The stimuli consisted of grey-scale rendered images of 3-dimensional target objects embedded in 3-dimensional multi-scale noise (Perlin noise). The detection of a target object was measured when presented alone or in the presence of flanking objects that had similar or different shape or similar or different part-configuration to the target object.

Chapter 3 – Is the detectability of a Gaborized contour modulated by the presence of nearby flanking contours?

The purpose of this set of experiments was to identify the basic effect of the presence of shape contours present in the periphery (flankers) on the contour detection/integration of a target shape contour. These flanking contours could be similar or different or may only share some feature of the target shape (e.g., symmetry).

The experiment was done using a standard approach in contour integration studies, where the detection of Gaborized contour embedded in a noise field of similar randomly oriented Gabors was disrupted by adjusting the local orientations of Gabor patches belonging to the target contour.

Chapter 4 – Contour integration is facilitated by the presence of adjacent contours that share shape-level features.

The purpose of this experiment was to determine the importance of specific shape features on both the detectability of the target contour and the subsequent facilitation of the detectability of the target when surrounded by flanking contours of the same shape. This experiment investigated the role of recognisability and symmetry on the facilitator effect of flanking contours on the detectability of a central

Gaborized target.

The standard introduction of orientation noise increases the complexity of a target Gaborized contour until it can no longer be detected. However, before the addition of orientation noise the Gaborized contours were of varying initial shape complexity. Hence, performance differences were not captured by the simple investigation of the detectability of the target contour. Both these effects were investigated by devising a method that took into account the holistic shape changes that occurred to a virtual perimeter that would result if the visual system was extracting a smooth contour from the misaligned Gabor patches.

Chapter 5 – The magnitude of the flanker facilitation effect on contour integration is modulated by changes in spatial location and numerosity of flanking contours.

The purpose of this set of experiments was to investigate the importance of contextual factors such as numerosity and alignment on the magnitude of the flanker facilitation effect. The spatial relationships of the flanker and target Gaborized contours were compared in two experiments by increasing the number of flankers and changing the relative alignment of the flankers with respect to the target contours to identify contextual factors that modulate the strength of the flanker facilitation observed in the previous experiments.

Chapter 6 – Shape similarity modulates the magnitude of the flanker facilitation effect.

The target and flanker contours were presented in discrete groups based on the level of correspondence between the shape and feature of each contour. This set of experiments sought to determine whether the flanker facilitation effect was a specialised perceptual mechanism that functioned in specific conditions in which exact correspondences between flanker and targets were present, or a general mechanism in which different levels of similarity between contour shapes would produce different levels of the flanker facilitation effect.

Chapter 2

Is the detectability of a 3-D object embedded in multi-scale noise affected by the presence of neighbouring objects? (Pilot experiment)

2.1 Abstract

The detection of a whole object is a complex process in which the organization and visual details of the object's parts can modulate how easily the visual system performs detection tasks. However, a number of experiments have demonstrated that the perceptual processes that underpin object detection are modulated by other objects in the visual field. This pilot study investigated whether the detectability of a 3-D object embedded in multi-scale noise was affected by the presence of other flanking objects with shared or dissimilar part configuration and shape. In order to do this, a family of 3-D objects was generated by varying the shape and configuration of the object's parts. The image of the target object was embedded in a random multi-scale noise field that masked visual information across different spatial scales. A 2-AFC adaptive staircase procedure was used in which the visibility of the target object was decreased until participants were no longer able to detect the object. To do this, the opacity of the multi-scale noise, with respect to the embedded object, was increased or decreased. The target was presented by itself in a control condition or was flanked horizontally by a second object of similar or dissimilar configuration of parts or overall global shape. Preliminary results indicated that the presence of flanking objects decreased the detectability of the target object. However, the identification of a number of methodological issues associated with both the stimulus and the experimental procedure prompted a reevaluation of the approach used in this pilot study to address the questions that motivated the experiment.

2.2 Introduction

Objects can take a variety of complex forms - crumpled clothing, a cat curling up or moving, an insect the shape of a leaf, or even a rock. The capacity of the visual system to be able to detect and encode such a variety of complex shapes is thought to be underwritten by the visual system's sensitivity to a variety of high-level and low level features, such as symmetry (Mach, 1885/1959; Delius & Nowak, 1982; Bornstein et al., 1981; Wagemans, 1995; Treder et al., 2011; de Kuijer et al., 2004; van der Helm & Leeuwenberg, 1996; Friedenberg, 2000; van der Helm & Leeuwenberg, 2004; Treder, 2010); aspect-ratio (Zusne & Michels, 1962a; Regan & Hamstra, 1992); contour convexity/concavity (Koffka, 1935; Kanizsa, 1976; Bertamini & Wagemans, 2013; Huttenlocher & Wayner, 1992; N. Rubin, Pao, & Gieger, 2000; Pao & Geiger, 2001); circularity/compactness (Zusne & Michels, 1962a; Gallant et al., 1993, 1996; Wilkinson et al., 2000; Wilson & Wilkinson, 1998; Dumoulin & Hess, 2007); viewpoint (Tarr & Pinker, 1989; Jolicoeur & Milliken, 1989; Moses, Ullman, & Edelman, 1996; Vetter & Poggio, 1994; Palmer, Rosch, & Chase, 1981; Koenderink & Van doorn, 1979; Tarr & Kriegman, 2001); and the arrangement of the parts of an object (Rensink et al., 1997; Bertamini & Farrant, 2005; Hoffman & Singh, 1997; Keane et al., 2003).

However, the detection of the presence of whole objects is more complex than registering the set of visual details. Keane et al (2003) demonstrated that the sensitivity to changes in the arrangement (also known as the configuration of the object) or the shape of an object's parts was dependent on the types of change being presented. For instance, the replacement of an existing object part with a novel part (e.g., a spherical curved part replaced by a pyramidal, straight part) were less likely to be detected than changing the relative position of a part in the object. This suggests that the visual system encodes and responds to the overall configuration of an object more readily than the specific local details across the whole object.

In contrast, the early visual system is also involved in integrating purely localized information such as contrast, orientation and curvature into the edges and boundaries of the object. (Wallach, 1935; Attneave, 1954). To do so, neurons are specifically responsive to localized and orientated contrast information (Hubel & Wiesel, 1959, 1962; Marcelja, 1980). The visual system can then, in turn, detect whole shapes amongst sets of these discrete regions of local information (Wertheimer, 1923; Field et al., 1993; Barlow & Reeves, 1979; J. Beck, Rosenfield, & Avry, 1989; Smits, Vos, & Van Oeffelen, 1985; Loffler, 2008).

These studies were primarily focused on the effects of shape level information on the local processing of a single object. Research into the simultaneous presentation of multiple objects and features has demonstrated that the detectability of a single target is dependent on contextual factors introduced between objects. For 2-D contours, for instance, peripheral unattended contours become more detectable when presented simultaneously with primary centrally attended contours when both share a specific feature (Stojanoski & Niemeier, 2007).

The studies described here demonstrate that the presence of specific features play a role in the detection of a central target. In turn, the presence of features in an attended central object can facilitate peripheral objects if they share the feature in common with the initial target object. However, a number of other, more specific enhancements have been observed that are linked to the presence of both multiple objects and other sensory cues.

In a perceptual effect, known as the 'redundancy signals effect' (Todd, 1912; Miller, 1982), the speed of detecting a target stimuli was shown to be more rapid when it was presented with additional sensory information. To study this perceptual effect these studies show how rapidly an observer can detect a target both with and without the presence of a different sensory cues. For example, when an observer is asked to detect either a brief auditory tone or light, they perform the detection of the light more quickly (in comparison to detecting the light alone) when both the tone and light are presented simultaneously.

Similar effects have been observed in the visual mode alone when two or more feature dimensions are presented together (e.g., colour, orientation or semantic meaning of a shape) in the context of a visual-only detection task (Krummenacher et al., 2001, 2002a; Ben-David & Algom, 2009; Toellner et al., 2011).

In addition to the redundancy signals effect, the simultaneous presentation of stimuli has been observed to enhance the sensitivity of the visual system to low level information. For instance, Mundy et al (2007, 2009) demonstrated that observers become more sensitive to the differences between two otherwise identical checkerboard patterns when they were shown simultaneously side-by-side. This enhancement was shown to be greater than the ability of an observer to detect the difference between the two patterns when they were presented sequentially.

Though objects occur independently in the environment and have unique projections onto the retina, the evidence accrued in the research thus far has demonstrated that the performance of the visual system in detecting an object is a highly complex set of contextually sensitive processes that can enhance the detection of both intentionally targeted, as well as peripheral, objects.

An unanswered and important question is whether having other objects in the surrounding regions enhances or suppresses the local perceptual mechanisms responsible for visual detection (e.g., in a similar vein to the effects of bilateral symmetry on the perceptual organization of a contour). Such visual interactions are particularly evident in a variety of visual depictions.

One such example is the depiction of a sequence of objects that represent a causal change (such as Escher's etchings, or, Worthington's scientific drawings (Worthington, 1894) shown in Figure 1.1, p.6). In such cases one automatically perceives a grouping that is dependent on systematic changes in part structure. These types of interactions imply not only that neighbouring objects could influence the visual processing of an individual target object, but also that such interactions may be dependent on similarities and differences in part structure.

2.3 Aims

Previous research has provided some evidence showing the visual system to be sensitive to the additional features and objects surrounding a target object. Secondly, the simultaneous presentation of multiple related patterns enhanced the sensitivity to local differences between such patterns. Finally, such processes have been shown to be sensitive to the configuration of an object.

The primary goal of this methodology was to investigate whether the commonalities in the configuration of the objects facilitated detectability of similar objects in the visual field. To preserve the overall configuration of the object while disrupting the local features the experiment involved a novel application of a classic multi-scale fractal noise generation procedure (Peachey, 1985; Perlin, 1985). (see Appendix 1 and 2, p.200 and 202). The target object was embedded in a random luminance multi-scale noise image. Due to the nature of this so-called Perlin noise, this would effectively result in obscuring the luminance information of the target object at multiple scales. The resultant image appears as a 3D object embedded in a 3D ′noise cloud′.

The detectability of the target object was measured by decreasing the visibility of the object with respect to the multi-scale noise. Specifically, the target object bitmap image was combined with a Perlin multi-scale noise image of the same pixel dimensions by averaging the pixel luminance values from each image (object and noise image). A visibility decrease corresponded to a greater luminance contribution from the multi-scale noise, than the object bitmap image, to the pixel value in the resultant stimulus.

The displayed stimuli consisted of a central target object with or without the presence of other flanking object in the region surrounding the target object. The flanking objects either visually matched the target object (had corresponding parts and part configuration) or differed (the parts or part-whole configuration differed between target and flankers).

Participants were required to detect the presence of a central target object in a 2-AFC procedure. The aim of the experiment was to determine whether the detectability of a target object was facilitated or suppressed by the presence of flanking objects. In turn, the object stimuli were generated to test the effects of the overall shape and the configuration of parts under such conditions.

One consequence of an object being embedded in scaled noise under these experimental conditions is that the visual system must first extract the local information to perform the detection task. Hence, any observed effect on detectability by the presence of flanking objects could indicate that the additional objects alters local contrast processing or global shape detection processes. An identification of any detection advantage could then be used to examine how such mechanisms may operate.

2.4 Methodology

2.4.1 Participants

4 participants (ages 22-30) performed the experiment. Each participant performed one session of 1 hour. A break was provided mid-way during the session for as long as the participant wished. All participants had normal or corrected-to-normal vision. The St Andrews University Teaching and Research Ethics Committee (UTREC) granted ethical approval (Ethics reference number: PS7638). The participants were asked to report any impressions of the experiment with regard to difficulty or ease in post-experiment de-briefing.

2.4.2 Apparatus

Experiments were run on a Dell 2407WFP running a LCD display with a resolution of 1920x1200 and a refresh rate of 60Hz. The viewing distance was 57cm. Participants viewed the screen from a chin/head rest. The experiment was implemented using C++ with the OpenGL library.

2.4.3 Stimuli

During an individual trial two stimuli corresponding to target-present and target-absent were presented sequentially. Each stimulus consisted of one or two 3-D objects (Object images) embedded in multi-scale noise (Noise images) that covered a rectangular area of 13 by 10 arc degrees placed on an otherwise black screen.

Object Images

3-Dimensional object stimuli were generated using the 3D modelling utilities provided by PovRay (of Vision Pty. Ltd, 2004) (For details of the procedure see Appendix 1. p.200). Objects were generated under a single diffuse illumination. The projective parameters were adjusted so that the angle of the main vertical axis of the object with respect to the line of sight of an observer was set to 30 degrees. The viewing angle was chosen to provide visual presentation of the entire configuration of the objects. This angle was chosen to provide visual presentation of the entire configuration of the objects.

Each object generated consisted of four object parts connected to a central body. The central body was a cuboid and the individual object parts had volumes less than 1/2 of the central object body. The parts of the objects were configured to form a symmetric cross-shape.

Four base objects were generated that were subdivided into two groups. One group of target objects had a set of parts that were identical with each other; the individual parts of the second group of target objects were a set of additional randomized 3-D objects. The four initial objects are shown in figure 2.1. The groups were chosen so that the effects of changing the visual details of each part could be examined in future experiments.

The flanker objects could either be the same as the target object, different, or similar but with an altered configuration. A set of 8 objects with altered configuration were generated. These were based on the initial set of four target objects by varying the identity, or relative alignment of one or more of the parts of the object. For example, Figure 2.2 demonstrates the configuration variants for a single object. The first object has no adjustments to the initial configuration of the target object; the second

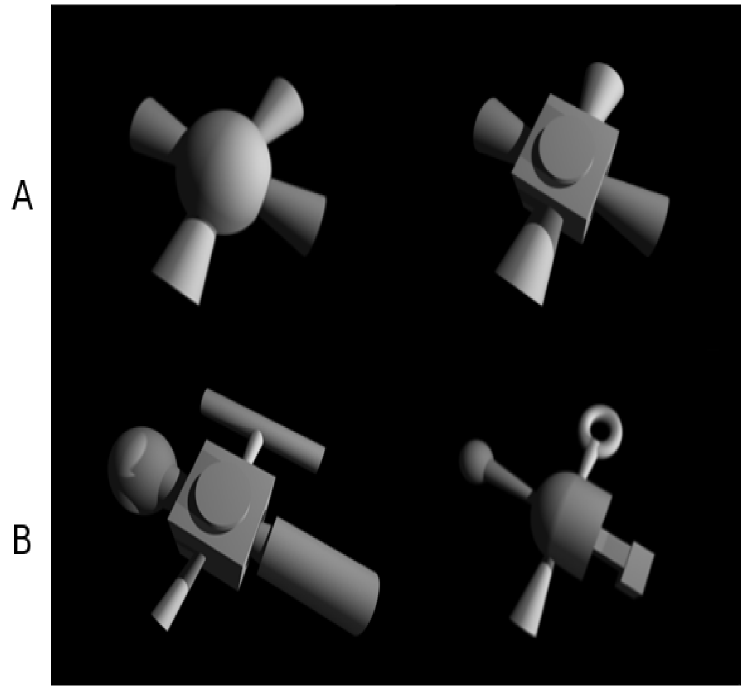

Figure 2.1: **Objects used as a detection target.**
Objects consisted of 4 parts arranged perpendicular to the center of the main object body which was a simple solid. With respect to the plan view from the top of the objects the object viewpoint was set along the x and z axis to permit viewing of all parts. Two groups of objects were generated: (Top left and right) One group of objects with identical parts (360 degree rotation symmetry along the depth plane). (Bottom left and right) A second group of objects with differing parts (without rotational symmetry). Both groups of objects were used as a basis from which an additional set of objects was generated.

object has a rotation of 30 degrees for a single part of the initial target object; and the third object has a rotation of 30 degrees for two parts of the initial target object.

This formed a group of 12 different possible flanking objects with 4 target objects combined with the 8 further similar objects with differences in the configuration of the object's parts.

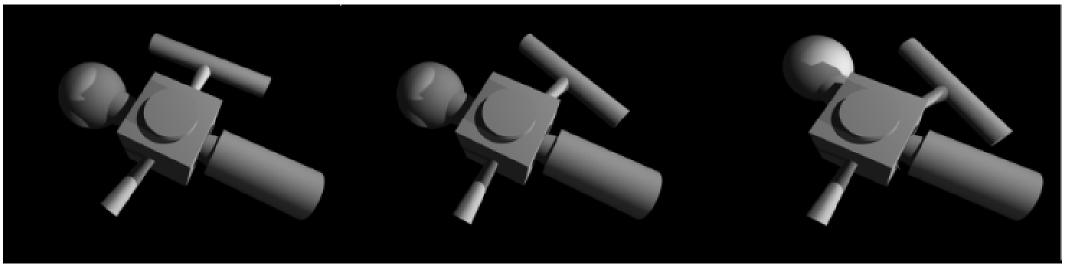

Figure 2.2: **Configuration changes for a single object.**
For each object two variations of the original object were generated by the rotation of individual parts from their original perpendicular orientation with respect to the main object axis. The set of individual objects consisted of (A) index object without adjustment to object parts, (B) similar 1, with the upper right part rotated by 30 degrees, and (C) similar 2, with the upper left and upper right parts rotated by 30 degrees.

Noise images

The noise images consisted of what is known as Perlin noise (Perlin, 1985) using a C++ Noise generator library (Bevins, 2003). The noise consisted of a randomized alpha value for a given pixel between 0-255, with 0 being black and 255 being white. The generation of this multi-scale fractal noise is described in Appendix 2 (p.203).

Each noise image consisted of an area that subtended a region of 13 by 10 arc degrees when presented onscreen. Multi-scale noise has a two primary parameters: (A) the number of frequency harmonics for the noise image can be increased or decreased, this is described as the octave value of the multi-scale noise, and (B) the relative amplitude of the frequency harmonics are altered, this property is known as persistence.

Figure 2.3 demonstrates changing the maximum frequency occurring in each noise image. Increasing the maximum frequency increases the level of visual detail for the image. Figure 2.4 shows the increase in the octave number. The increase in the octave value increases the number of included frequency harmonics in the image.

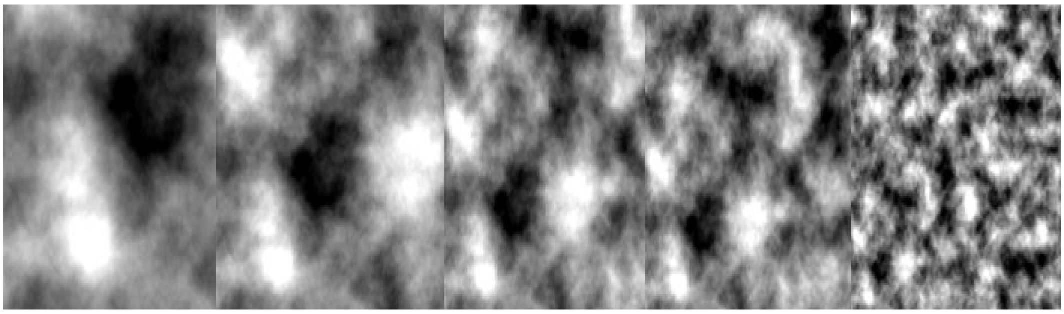

Figure 2.3: **Example set of multi-scale noise with varying maximum frequency harmonics.**
Different maximum frequency component used to obscure target. The noise was generated by varying the pixel level value between 0 (white) and 255 (black). The harmonics added to a single noise image were based on a maximum frequency to which the additional harmonics were related. An increase in the maximum frequency value corresponded to increases in the amount of sampled noise across increasingly local regions. The examples of multi-scale noise presented have the maximum frequency components of (A) 2 (B) 2.5 (C) 4 (D) 5 (E) 10 Hz.

Perceptually this corresponds to an increase in the apparent resolution of the image. Finally, Figure 2.5 demonstrates an increase in the Persistence value of the image. The overall perceptual effect is to increase the contrast of the individual pixels across the whole image.

The noise images used in the experiment are shown in Figure 2.6. The initial parameters were restricted to a range of three frequency intervals of 1, 2 and 4 Hz. The persistence and Octave values were restricted to 0.2 and 6 respectively for this experiment. These values created a noise image with a reasonable contrast and level of detail.

Stimulus Images

The stimulus presented in each trial was generated by combining the pixel values of the object and noise images. Specifically, the alpha value of a given pixel was

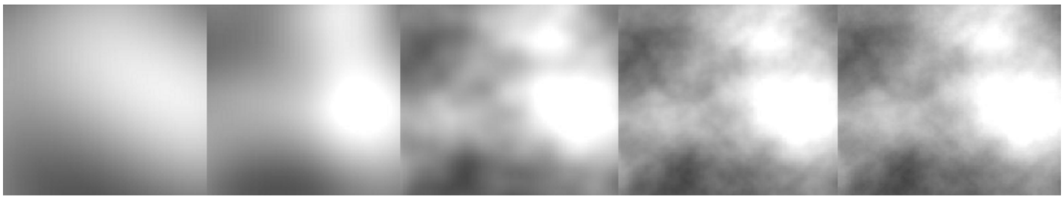

Figure 2.4: **Example set of multi-scale noise with increasing numbers of higher order octaves of a single frequency component (a.k.a., octave value) added to a single multi-scale noise.**
Each noise image consisted of a number of frequency harmonics. These harmonics were measured as an octave. The number of octaves could be increased or decreased and further frequency harmonics were added to the noise image. With larger numbers of frequency harmonics there was a wider number of pixels generated per area. In turn, it is perceived as an increase in the resolution of local features. For a noise panel with a minimum frequency of 1Hz the number of octaves in the noise is: A) 1 (B) 2 (C) 4 (D) 5 (E) 6 octaves.

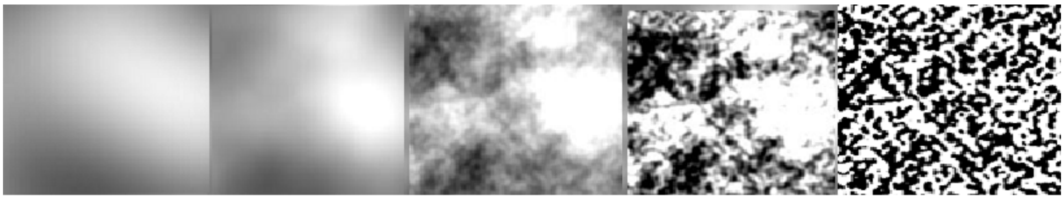

Figure 2.5: **Example set of multi-scale noise with persistence values.**
The persistence value relates the amplitude of each subsequent frequency harmonic in the multi-scale noise (a decrease in persistence reduces the amplitude of higher frequency noise). For a noise image presented here with a minimum frequency of 1Hz the number of persistence in the noise is: (A) 0.1 (B) 0.2 (C) 0.6 (D) 0.8 (E) 1

determined by a weighted averaging of the pixel value in a given object image and noise image (see Figure 2.7). Varying the relative weighting of the pixel contribution of the object and noise images created stimulus panels of different object visibility.

An increase in the contribution from the object image effectively corresponded to an

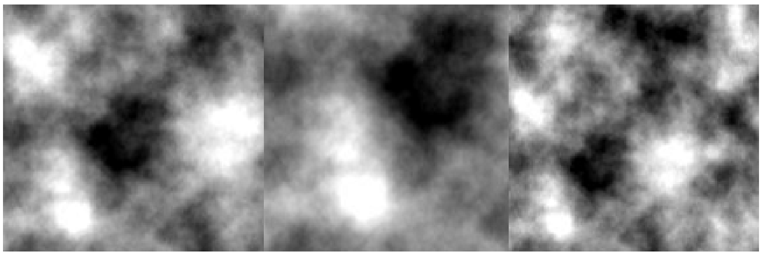

Figure 2.6: **The Multi-scale noise used to obscure target.** Each object for every condition was embedded in three different images with different frequencies of multi-scale noise. They were (A) 1, (B) 2, and (C) 4 and are presented above. The samples were generated with a persistence value of 0.2 and an octave number of 6 in all cases.

increase in the transparency of the noise. Conversely, an increase in the contribution from the noise panel corresponded to an increase in the opaqueness of the noise. The opacity was defined as the normalized ratio of the weighting of the noise-image alpha values to the object-image alpha values.

The detectability of the target contour was defined as the opacity of the multi-scale noise (the weighting of noise panel to pixel values) at which a participant could no longer detect the object. The opacity was increased or decreased by an opacity interval value of 4. The overall range of opacity was restricted to the range of values between 0 to 40 percent, where 0 percent represents completely opaque noise (object fully obscured) and 100 percent a fully visible object with no contribution of noise.

Four conditions were created to determine the effects of the flanker objects on the detectability of the object: (A) control condition, in which no flanker is present, (B) same condition, in which the target object was paired with flanker with the same shape and configuration (C) similarity condition, in which the target object was paired with a flanker from the same overall shape but with different configuration (D) different condition, in which the flanker object was different in shape from the object. These conditions are presented in Figure 2.8.

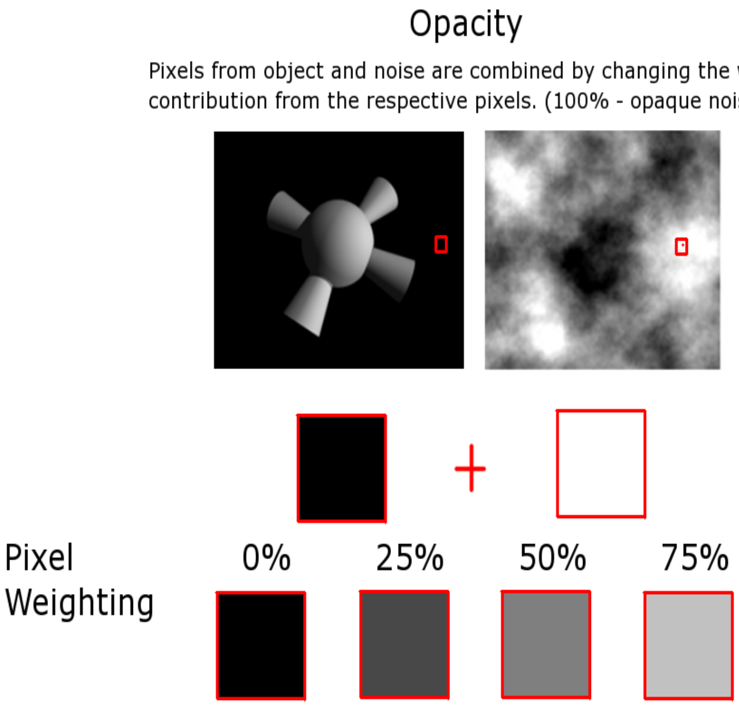

Figure 2.7: **The dependent measurement was a change in the opacity of a noise image with respect to a target object.**
The detectability of the target object was measured by varying the contribution of the noise and object to an individual pixel. The pixel values corresponding to the object and the 3-D noise were added per pixel by taking a weighted average. The weight was varied to reduce the contribution of the object relative to the noise. This reduced the overall appearance of transparency of the noise and the object become less visible.

A 2-AFC procedure was used in which the sequential presentation of either a target-present panel or a target-absent panel occurred randomly on the left or right hand side of the monitor. The target absent panel was otherwise identical to the target present panel except that there was no target object present.

A final inter-trial display panel was presented after the two stimulus panels were shown. These inter-trial display panels consisted of a noise image combined with a

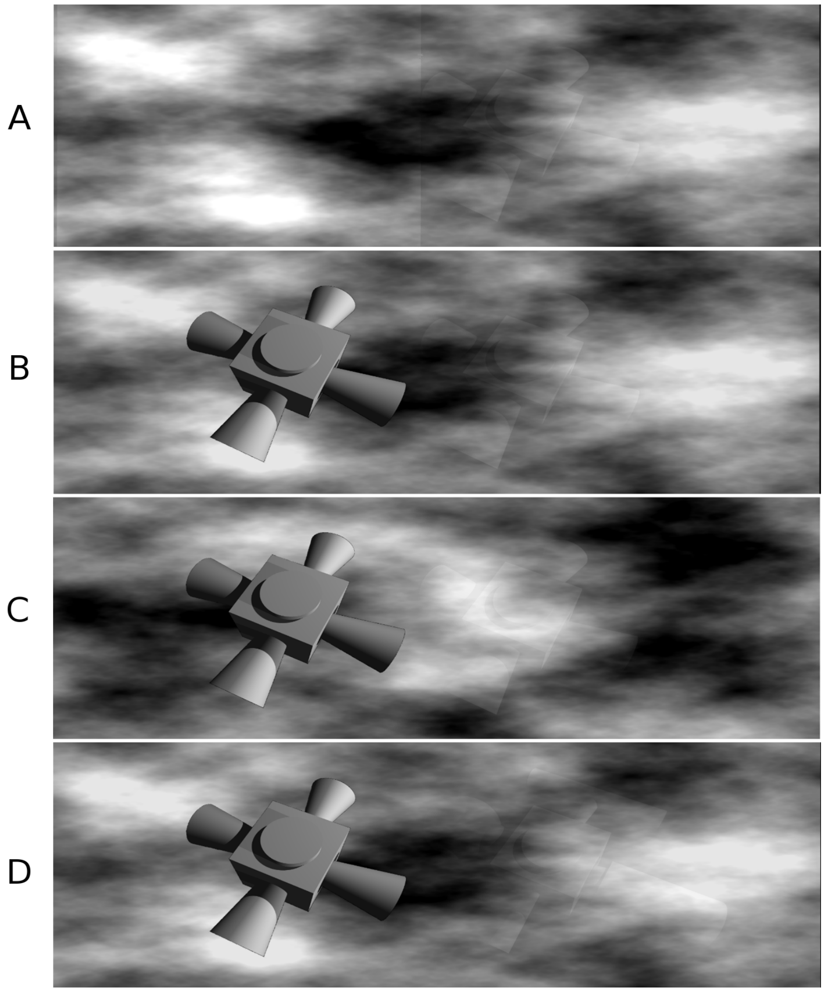

Figure 2.8: **The four conditions tested in the pilot experiment.** The above figure presents the four conditions presented to the participants. The target is presented near the detection threshold (e.g., less visible). The conditions were: (A) a control condition, in which a target object was presented alone in a control condition with no flanker (B) a same condition, in which the target is presented with a flanking object of the same shape (C) a similar condition, where the flankers are a modified version of the target object (D) a different condition, where a target object is presented with a flanking object of a different shape.

randomized version of a target image where the images was segmented into a grid of 10x10 pixels and the individual patches randomly repositioned.

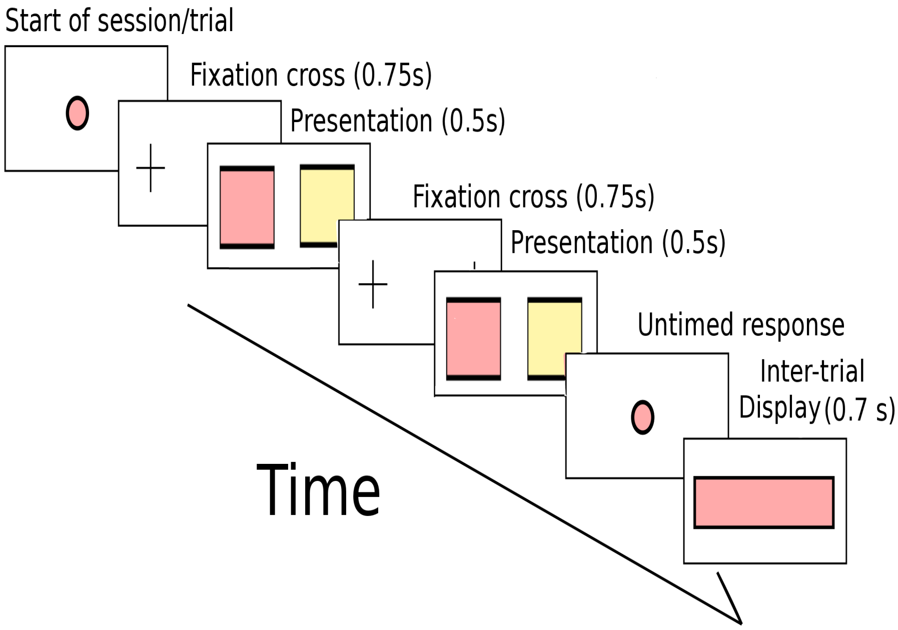

Figure 2.9: **The time course for a single trial.**
The stimulus consisted of the sequential presentation of two panels, one of which contained the target object. The stimuli were randomly presented in either the left (red) or right (yellow) side of the monitor from trial to trial. Each presentation consisted of an initial fixation cross that directed the observer's attention to the panel location, this was followed by one of the stimulus frames. Each stimulus frame was either a target-absent or a target-present image. Once the two stimulus frames were presented, a red circle appeared that prompted the subject to indicate in which stimulus frame (first or second) they saw a target object, this circle remained until the observer made a response. Finally, an inter-trial display image was presented

2.5 Procedure

The sequence of stimulus presentation (see Figure 2.10) involved an initial fixation circle at the center of the main display panel (750 ms). A second fixation cross was randomly presented in either the left or right hand side of the screen. This was followed by the presentation of either a target-present or target absent stimulus panel for 500 ms. After this duration elapsed a fixation cross appeared at the opposite location (right or left of the display panel) and was followed by either the target-absent or target-present panel (depending on what was previously shown). Finally, a red circle was presented in the center of the main display panel with no fixed duration. The observer was asked to respond if an object was present in the target region in either the right or left panel. The opacity was varied according to participant responses using a 1-up 1-down staircase procedure. The initial level of opacity for each staircase was at the lowest (40 percent) value possible, that is, when the object was most visible. The detection threshold was defined as the level of opacity at which the participant was no longer able to detect the shape. Each staircase was terminated after 50 trials and the threshold was calculated by taking the mean value over which the last 5 reversals that took place.

2.6 Results

In order to determine if there was an overall effect of the presence of flankers on contour detectability, the detection thresholds for each stimulus condition (control, same, similarity and different) were averaged over all target objects. These mean detection thresholds are shown in the bar plot in Figure 2.10.

The detection thresholds were highest for all conditions when the target object and flanking objects were the same as the target object. In other words, in comparison with the control condition, the target object was less readily detectable to the participants. This was also true for target objects paired with flanking objects that were different in overall visual identity. However, in comparison, the detection thresholds for the similarity condition was neither more nor less than that of the control condition. Hence, the presentation of objects that were either the same or different showed suppressive effects on the target detectability. This was not true for the similarity condition in which the target object was as detectable as when it was presented alone.

During the data collection for the pilot experiment, participants were required to provide feedback on the difficulty of the task and any other issues that were noted.

Notably, the participants reported having issues adjusting their gaze to the 1st stimuli panel and that they missed the presented panel. There were too few participants for statistical analysis and based on their observations the experimental stimulus and methodology was reevaluated and a number of further perceptual and methodological problems were identified.

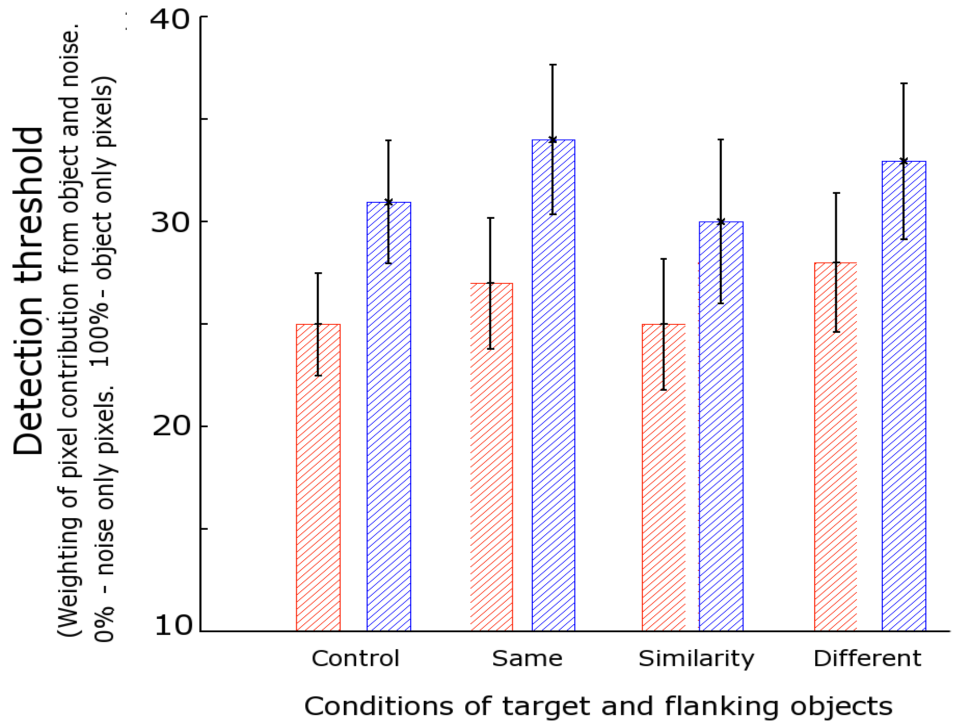

Figure 2.10: **The mean detection thresholds for the experimental conditions for objects with identical parts (Red) and Non-identical parts (Blue).**

Detection thresholds (opacity at which the target was no longer perceived) for the target-flanker conditions. The plotted conditions are the control condition (no flanking object); the same condition (target and flanker have the same configuration and shape); the similarity condition (target and flankers are the same group of objects with an adjustment made to the configuration of the flanker) and the different condition (the target and flanker objects are different). The plotted data are the opacity of the noise relative to the target at a detection threshold of 50 percent proportion correct averaged over all participants (n=4). Error bars represent the standard error of the mean

2.7 General Discussion

The purpose of this pilot was to do a preliminary examination of the role of the presence of extraneous objects on the detection of a target object. The goal was also to validate the choice of stimuli and methodology. The specific experimental goal was to determine if the presence of additional flanker objects in the surrounding region of a target object affected the detection of the target object. In particular two factors were examined: (1) the identity of the flanker (whether it was similar or different in shape to the target) (2) the relatedness of the flanker (how similar its parts were to the target in terms of identity and configuration). Overall, the initial results indicated that the detectability of the target object was lower for objects with similar flanking objects and, in turn, lower in the same and different conditions. However, the validity of these results was deemed questionable due to a number of design and methodological flaws that were identified.

2.8 Issues related to task procedure

The methodology involved the random presentation of a fixation cross and the stimuli on either the left or right hand side of the monitor screen. In the debriefing period a number of the participants reported that they found tracking the position of the fixation cross and the subsequent presentation difficult. This led them to frequently miss the object in the first panel presentation. In addition to this, a potential factor was the presence of the flanker object. In the course of the experiment, the participants may have made saccades over the flanker objects when targeting the central object. Hence, participants could spend less time looking at the target region. Any observed suppressive effects of the presence of flankers could also be attributed to the unavoidable effects of the eye movements required to shift gaze between panels.

2.9 Issues related to the stimulus

In the process of examining the stimuli in further detail, it was also noted that sequential runs of stimuli with similar opacity values appeared to produce a motion-like effect. More specifically, by presenting a number of noise images in succession the target object embedded in the noise generated an illusion in which the object appeared to recede relative to the noise image as the opacity of the noise decreased. Methodologically this was problematic as it represented an unknown and confounded perceptual effect that was unaccounted for. This effect may be related to the multi-scale noise. This experimental strategy was novel and untested in this context. The primary advantage of using this type of noise was that it allowed the experimenter to disrupt lower order features associated with the target objects while maintaining the overall visibility of higher level features such as configuration.

However, one significant disadvantage was that the number of parameters available (e.g., frequency harmonics, individual amplitudes, as well as the relative amplitudes) increased the complexity of the stimuli. As the multi-scale noise was untested and contained a large number of co-dependent parameters that were interacting with the target object it was decided that it was, at this stage, uninterpretable. That is, though the detectability of the target object may have been increased or decreased by the presence of a flanker without constraints, without understanding how the multi-scale noise parameters were filtering the lower level features it was not possible to rule out confounding effects of such features on the detectability of the target object.

Multi-scale noise is an interesting and useful methodology that is worth investigating further. One of the most intriguing uses of this type of noise in psychophysical experiments is that, owning to the arbitrary dimensionality of multi-scale noise, a very large number of local features with different spatial characteristics can be controlled for in a single instance. However, more research is required to characterise the effects of varying persistence and octaves on the detectability of objects.

2.10 Conclusion

In light of the above concerns, the overall stimuli and methodology for the thesis aims was reevaluated. A new approach was devised by reducing the dimensionality of the target and flanker objects. In addition, the relationship of the detectability of a target and the specific features being disrupted using noise was reconsidered for the subsequent studies.

Chapter 3

Is the detectability of a Gaborized contour modulated by the presence of nearby flanking contours?

3.1 Abstract

The detection of a object in the visual field involves a set of complex perceptual processes that permit the visual system to integrate a variety of local visual features into a single whole object. This set of experiments investigated how the process of detecting an object is affected by the presence of other nearby objects. To test this, the detectability of a central target object - in the form of a two dimensional Gaborized contour - was compared in the presence or absence of nearby surrounding objects. These flanking objects, also two dimensional contours, contained similar or dissimilar shape profiles to the target object. The whole set of contours was generated using shape profiles of everyday objects and geometric forms. A 2-AFC experimental procedure was used to determine the detectability of the contour. Two displays containing randomly oriented and positioned Gabor patches were presented sequentially, one of which contained the target Gaborized contour. A detectability threshold for the target contour was determined using an adaptive staircase procedure in which orientation noise jitter was added to the target contour until it was no longer detectable by an observer. The detectability of the target contour in the presence of flankers of similar or dissimilar shapes was compared to the control condition in which the target contour was presented alone. The first experiment showed that the detection of a target contour was facilitated by the presence of flankers with the same shape as the target contour. However, additional diagnostic comparisons of the performance of individual contours suggested that this facilitatory effect might be affected by factors such as the visibility of the flankers and properties of the target shape such as symmetry. A second experiment investigated the role of symmetry and flanker visibility on the observed facilitatory effect. While a general facilitatory effect of flankers was replicated in this experiment, the interaction of factors such as shape symmetry, similarity and flanker visibility suggests a complex process that is dependent on both shared global shape and local contour information.

3.2 Introduction

The detection of an object in a scene and its subsequent recognition by the visual system are important perceptual processes. The process of detecting an object requires the visual system to extract and organize local visual information (such as contrast, orientation, etc.) into a single discrete object (Wallach, 1935). A consequence of this process (known as shape segmentation) is that the detection of a shape can occur even when minimal and spatially separate information is presented, as is the case for line drawings composed of broken up segments (Attneave, 1954).

A large number of studies has shown that the presence of specific regularities in the shape of an object aid the process of detection and recognition. Shape-level features such as shape symmetry (Mach, 1885/1959; Attneave, 1954; Delius & Nowak, 1982; Bornstein et al., 1981; Wagemans, 1995; Treder et al., 2011; de Kuijer et al., 2004; van der Helm & Leeuwenberg, 1996, 2004; Friedenberg, 2000; Treder, 2010; Baylis & Driver, 2001; Machilsen et al., 2009); shape aspect-ratio (Zusne & Michels, 1962a, 1962b; Regan & Hamstra, 1992); part/whole relationships in the object (Rensink et al., 1997; Bertamini & Farrant, 2005; Hoffman & Singh, 1997; Keane et al., 2003); and the contour convexity/concavity along the edge of an object (Koffka, 1935; Kanizsa, 1976; Bertamini & Wagemans, 2013; Huttenlocher & Wayner, 1992; N. Rubin et al., 2000; Pao & Geiger, 2001) have all been shown to be important psychophysical factors with respect to the detection of the presence of an object by the visual system.

Objects are rarely viewed from the same place. This leads to shape differences in the projection of an object onto the retina. The visual system differentially encodes specific viewpoints of objects, and due to this, both the complexity of the projected shape and the familiarity with the viewpoint have been observed to effect detection (Tarr & Pinker, 1989; Jolicoeur & Milliken, 1989; Moses et al., 1996; Vetter & Poggio, 1994; Palmer et al., 1981; Vetter & Poggio, 1994; Koenderink & Van doorn, 1979; Tarr & Kriegman, 2001). The contextual relationships that arise from the relative locations of objects in a scene can create new regularities, such as symmetries between objects. Like the features of a single object, the visual system is tuned to the detection of a number of these inter-object features (Koning & Wagemans, 2009; Baylis & Driver, 1995, 2001; van der Helm & Treder, 2009; Bertamini, 2010).

The visual system does not simply passively receive information from a single viewpoint, but can actively allocate and direct attention in the scene to maximise the possibility of detecting a specific target (Posner et al., 1980; McMains & Somers, 2004; Baylis & Driver, 1989, 1992; Duncan & NimmoSmith, 1996; Rossi & Paradiso, 1995; Duncan, 1984; Martinez et al., 2007; Kravitz & Behrmann, 2011). The allocation of attention to specific locations, objects and features in the visual field has a complex role in object processing with enhancements to the detectability and appearance of an attended target object (Cameron, Tai, & Carrasco, 2002; Carrasco, Ling, & Read, 2004); as well as the inhibition of the detection of a central and prominent object when attentional resources are allocated to a number of objects in a single scene (Levin & Simons, 1997; Simons & Chabris, 1999).

More generally, such dynamic changes in viewpoint and attention can lead to perceptual situations in which features and objects occupy adjacent regions. Simple spatial proximity of distractor objects and features immediately outside the focus of attention have been shown to inhibit the central target the observer is fixating on. In one such effect, the detection of the contrast of a small part of the visual field is modulated by differences in contrast with the region surrounding the target (Tadin et al., 2003; Born, 2000; Pack et al., 2005; Churan et al., 2009; Petrov et al., 2007; Spillmann, 1994; Troncoso et al., 2007). Hence, local features are sensitive to the features of adjacent regions.

A second conceptually similar but unrelated perceptual effect (Petrov et al., 2007) known as crowding has been observed in which the identification of a specific local feature of an object such as orientation is inhibited by the presence of adjacent distractor objects (Bouma, 1970; Stuart & Burian, 1962; Pelli & Tillman, 2008; Toet & Levi, 1992; Levi, 2008; Levi et al., 2002; Parkes et al., 2001; Pelli et al., 2004). On the other hand, facilitatory effects have been observed with the detection of a low contrast target Gabor patch becoming more efficient when paired with other higher contrast flanking Gabor patches (Polat & Sagi, 1993; Adini et al., 1997; Bonneh & Sagi, 1999; Cass & Spehar, 2005; Chen & Tyler, 2001; Freeman et al., 2001; Huang & Hess, 2007; Mizobe et al., 2001; Katkov & Sagi, 2010; Polat & Tyler, 1999; Sterkin et al., 2008; Woods et al., 2002; Zenger & Sagi, 1996).

On a global level the ability to detect such local changes in larger patterns (e.g., checkerboard patterns) is facilitated to a greater degree when otherwise identical patterns are presented simultaneously than when they were presented alone or sequentially organised (Mundy, Honey, & Dwyer, 2007, 2009). The enhancement to the perceptibility of objects is not limited to large patterns, and a number of other perceptual phenomena have been reported. One such effect is the observation that the reaction times for a target were lower when a target was presented simultaneously with an extra 'signal' when compared with the reaction time for a single signal. This effect has been observed for both inter-modal (Auditory Tone and brief light-flash) and intra-modal (Colour and Orientation) detection (Todd, 1912; Miller, 1982; Krummenacher et al., 2001, 2002a; Ben-David & Algom, 2009; Toellner et al., 2011).

Multiple objects do not simply improve the instantaneous performance of the visual system but can also induce the encoding of mean, or ensemble properties (Alvarez, 2011). This enables an observer to make optimal judgments about the mean psychophysical features of a group of objects such as object size (Ariely, 2001; Chong & Treisman, 2003), orientation (Dakin & Watt, 1997; Chong & Treisman, 2003; Parkes et al., 2001) and the centroid position of the set (Alvarez & Oliva, 2008) without having a corresponding enhancement in the encoding of the single objects that make up the group.

These effects (specifically the visually linked behavioural results) have been linked to the neurophysiological effect of multiple objects or features being projected to a region of the retina corresponding to the same receptive field (Sherrington, 1906) of the same neuron(s). In this, the overall activity of the neuron associated with a single feature has been shown to cause an inhibitory response in which two or more features compete for the response of a single neuron (Kastner et al., 1998, 2001; Desimone & Duncan, 1995; D. M. Beck & Kastner, 2009; Joo et al., 2012).

However, more recently, in response to a contrast detection task, the presence of simultaneous identical high-level stimuli (photographic objects) surrounding a target region of varying contrast has demonstrated that the visual system can facilitate or increase the activity of such neurons in response to the presence of redundant visual information (Shim et al., 2013). Hence, the overall consequences of multiple objects and features may produce more complex neural behavior than has been traditionally thought.

The detection of a single object in a scene is a computational task performed by the visual system that is sensitive to a large number of contextual occurrences arising in visual scenes. However, prior to detection the visual system must first separate the individual local features that correspond to a single object and bind them together. The present set of experiments seeks to determine whether the numerosity of objects plays a role in these more local processes.

3.2.1 Local processing and Contour integration

The studies reported have shown that the presence of important objects and features allow the visual system to more efficiently detect and process simple targets such as contrast patches , simple letters, and complex images (such as photographic images). However, real individual objects are spread in extent across the visual field and depend on a large amount of complex local processing (Wertheimer, 1923; Wallach, 1935; Attneave, 1954).

In a previous pilot experiment, the role of the presence of additional objects to the detectability of a target object was examined. In order to make the test stimuli as naturalistic as possible, images of 3D rendered objects were embedded in a multi-scale luminance noise (Perlin noise) where the opacity of the noise at threshold detectability was as used the dependent measure. Further consideration revealed that this stimulus space was too complex and precluded systematic examination of local and global features in target detectability. In the present and subsequent studies, it was therefore decided to use a more well characterized space used in object detection, which utilized 2D object contours, and provided a more structured basis for examining the role of global and local features in detectability

Specifically, the experimental domain of contour integration was chosen (Wertheimer, 1923; Gilbert & Wiesel, 1979, 1983; Field et al., 1993; Barlow & Reeves, 1979; J. Beck et al., 1989; Smits et al., 1985; Loffler, 2008). This methodology allows the experimental manipulation of low level features (e.g., local orientation), low level processes (contour integration) and high level shape factors (symmetry and recognisability of the contour) simultaneously. Studies of contour integration are useful in determining the effects of global factors on local processing for a number of reasons. For instance, the neuronal responses of the v1 region to local features in the visual field have been shown to be highly selective to certain features (e.g., contrast, orientation) (Hubel & Wiesel, 1962, 1959) and this has been modelled using a type of luminance feature known as a Gabor patch (Marcelja, 1980).

Pyschophysically, the use of 2-Dimensional contours composed of Gabor patches are readily parametrized. For instance, in the case of the relative spatial and orientation of neighboring group of Gabor patches, the second order property of curvature can be quantified. The curvature and convexity of a contour has been shown to be selectively processed in regions beyond V1 (Blakemore & Over, 1974; Watt & Andrews, 1982; Hoffman & Richards, 1984). Furthermore, 2D contours allow simplified, quantifiable features that affect higher level processing to be introduced. Investigations have shown the role of a variety of shape-specific features on contour integration. One such factor is whether the contour is open (string−like) or closed (hoop−like), with closed contours being more detectable than open ones (Elder & Zucker, 1993; Kovacs & Julesz, 1993; Gerhardstein et al., 2012). Another shape feature - bilateral symmetry - has been shown to facilitate the detection of a contour, and correspondingly play a role in the perceptual organisation of the local information presented by Gabor patches across the visual field (Machilsen et al., 2009).

3.2.2 Experimental Summary

As described in the review above, the presence of multiple objects and features influences the detection of objects in a scene. An important factor involved in the detection process is how local visual information is bound together and separated from the scene as a coherent whole object. One methodology for investigating this process involves the use of localized, oriented contrast information in the form of Gabor patches that the visual system naturally integrates together into coherent contours. By varying the factors that promote such integration, it is possible to determine whether the presence of other nearby contour shapes, can also influence the integration of a target contour.

This study examined how the detectability of a central target contour embedded in a noise field of randomly oriented and positioned Gabor patches was affected by the presence of two horizontally flanking contours of similar or dissimilar shapes. Contour detection performance in such conditions was compared to control conditions where the target object was presented in isolation. Contour detectability was systematically degraded by the addition of orientation noise jitter to the individual Gabor gratings making up the target contour. Detection thresholds were defined as the maximum amount of orientation noise jitter that could be added to the contour before it became undetectable. Therefore, higher levels of orientation noise jitter indicated more enhanced levels of detectability.

Experiment 1 investigated the general effect of the presence of flanker contours on the detectability of a Gaborized target contour. Experiment 2a investigated whether the introduction of a region of isolinearly Gabor noise field in the flanking regions affected the detectability of a target consisting of a single Gaborized contour. This was done to establish the use of isolinear noise field in the periphery to enhance the perceptibility of the flanking contours in the second part of the experiment. Experiment 2b investigate the importance of bilateral symmetry of the target and flanker contours on the detectability of a target contour.

3.3 Experiment 1

The purpose of the first experiment was to examine the effect of the presence of two horizontally flanking contours on the detectability of a central Gaborized target contour. Target contours included random shapes and shapes of common objects that were either symmetric or non-symmetric.

3.3.1 Methodology

Participants

12 participants performed the experiment. 10 were paid undergraduate volunteers (£5 per hour) while 2 were postgraduate students who performed the task without payment. 8 of the participants were female. The participants were in the age range of 17 to 30 years old. Each participant performed two sessions (1 hour per session). A break was provided mid-way during the session for as long as the participant wished. All participants had normal or corrected-to-normal vision. Ethics was granted by the St Andrews University Teaching and Research Ethics Committee (UTREC - Ethics reference number: PS7638).

Apparatus

Experiments were presented on a Dell 2407WFP LCD display with a resolution of 1920x1200 with a refresh rate of 60Hz. The viewing distance was 57cm. Participants viewed the screen from a chin/head rest. The experiment was implemented using Matlab (Mathworks, Inc) using the psychophysics toolbox utilities (Brainard, 1997).

Stimuli

The stimuli were created using the Grouping Elements Rendering Toolbox (Demeyer & Machilsen, 2012) based on the Matlab programming language. The staircase procedure used to present the stimuli for each trial was run using the Palamedes Toolbox (Prins & Kingdom, 2001).

The stimuli consisted of two components: a set of sine waves windowed by a Gaussian envelope, known as a Gabor patch, and a generating shape combined with a set of Gabor patches to generate the stimuli presented to the observers. The Gabor patches consisted of a sine wave luminance profile of frequency 2 cycles/deg and the 2-dimensional Gaussian envelope with a Gaussian standard deviation (sigma value) of 3 pixels. The phase of each Gabor patch was randomised by 90 degrees.

The stimuli presented in the panels were presented on a grey rectangular panel (14x8 degree) which was placed on an otherwise black screen. The panel was primarily populated with a field of randomly positioned, non-overlapping, randomly oriented Gabor patches (referred to as the noise field). The average initial minimum spacing between Gabor patches in the noise field was around 16.5px.

The generating shapes for these Gaborized contours are presented in Figure 3.1. These were chosen to provide a set of contours with a range of features including familiarity (e.g. profiles of everyday object vs. random shape profiles), geometric regularity (e.g. symmetry) and complexity (e.g. random, irregular shapes).

The orientation of the individual Gabor patches corresponded with the local orientation of the underlying generating shape (Figure 3.2). The width of distance between each subsequent Gabor patch along the Gaborized contour was randomised. The maximum width to which subsequent Gabor patches could be positioned was a single wavelength. Inspections were made of the subsequent Gaborized contours and minor adjustments (+/- 2 Gabor patches) were made if the resultant contour lacked corners or extrema. The Gaborized contours were then embedded in the noise field

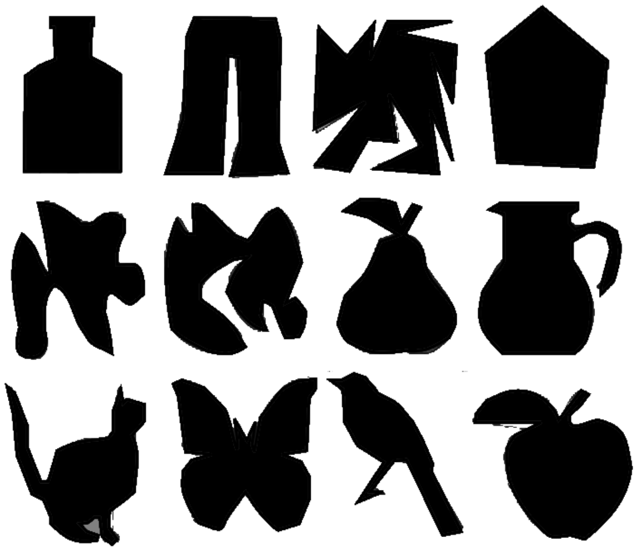

Figure 3.1: **Shapes used to generate target and flanker Gaborized contours.** Generating shapes consisted of both outlines of everyday objects (e.g., Cat, Jug, Trousers) and a set of geometric forms of varying regularity (e.g., Hexagon, Non-regular curvilinear shapes). The initial outlines consisted of shapes of: (From Left to right, Row 1 then Row 2 then Row 2) a Bottle, Trousers, J1, J2, S1, S2, Pear, Jug, Cat, Butterfly, Bird, Apple).

(Figure 3.3 and 3.4) such that there was no overlap with the noise Gabor patches.

The combination of the Gaborized contour and the noise field introduced possible variations in the density of the overall panel of Gabor gratings. To assess the presence of probabilistically significant density differences, and subsequently adjust the relative locations of the set of Gabor patches, a method native to the stimuli generating program, G.E.R.T, was used (Demeyer & Machilsen, 2012). This employed a Voroni tessellation to isolate the immediate area surrounding each Gabor patch and trace it as a polygon. The surface areas for the polygons were computed and compared across both the noise field and the embedded contours to determine that the surface areas were reasonably uniform across the whole stimuli.

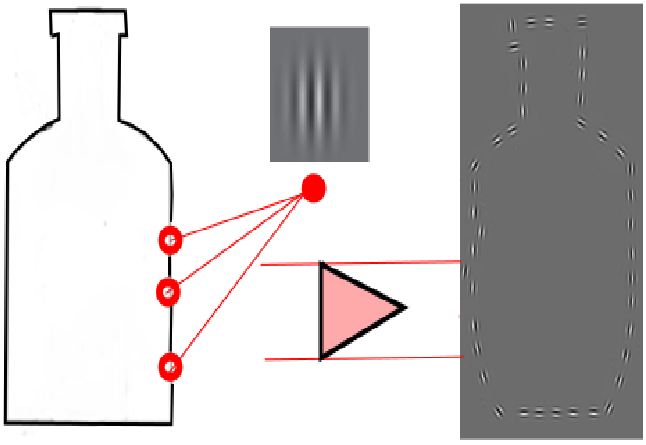

Figure 3.2: **Methodology for generating Gaborized contours**
The Gaborized contour stimuli were generated by combining pre-set shapes with a group of Gabor patches. The methodology for creating Gaborized contours involved taking a smooth shape and placing Gabor patches at random intervals along the path of the shape. The individual patches had their orientations aligned with the orientation of the line of the shape. The smooth shape was then removed leaving a Gaborized contour.

Detection threshold and conditions

The previous chapter (p.30) focused on the presence of 3-D objects presented within 3-D noise field. The visibility of the target was increased by making the noise more transparent. The detection threshold was a direct function of the degree of transparency. A lower detection threshold (higher perceptual sensitivity) was implicated when the target was detected at a lower degree of transparency (higher opacity of noise). However, in the current and subsequent chapters, noise is directly added to the object in question (a Gaborized contour). Thus, a lower detection threshold (higher perceptual sensitivity) is implicated when the target can be detected at a higher level of noise. In other words, in the previous chapter, lower detection thresholds (better detectability) corresponded to a lower value of the independent variable (transparency), while in the remaining chapters lower detection thresholds (better detectability) corresponds with higher value of the independent variable (orientation noise).

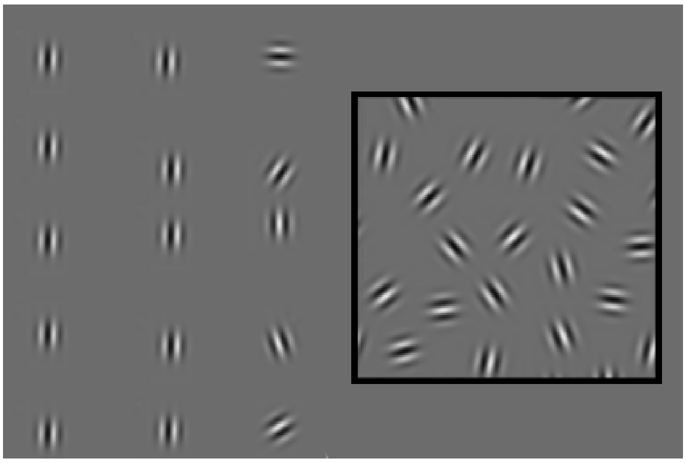

Figure 3.3: **Orientation and positional adjustments to Gabor patches**
The group of Gabor patches could be parametrized in two ways: the relative distance between each sequential Gabor patch along the contour, and the relative orientation of each Gabor patch. A set of Gabor patches that are both regularly spaced, and vertically aligned is presented in the far left. The relative spacing was varied by randomizing the distance between sequential Gabor patches by up to two wavelengths of the patches used. Finally, orientation jitter was used to decrease the alignment of adjacent Gabor patches. The absolute position and orientation was randomized for Gabor patches associated with the noise field (shown in the inset box).

The detectability of the target contour in a panel was altered by adding orientation noise jitter to the individual Gabors making up the contour. The amount of orientation noise jitter added across the set of Gabor patches making up the contour was sampled from a normal distribution centered on a particular mean value (e.g., 50 degrees away from local contour tangent alignment). The maximum value such orientation jitter could take was +/-90, i.e. orthogonal to the local tangent. In the set of experiment reported here and elsewhere, the dependent variable is reported as the magnitude of the orientation noise jitter (e.g., +/-90, corresponds to a magnitude of 180 degrees). For example, 40 degrees of noise jitter represented a highly visible contour with a low level of orientation noise jitter, while 120 degrees of noise jitter represented a contour with low visibility with a high level of orientation noise jitter. The effects of adding orientation noise to a smooth contour are presented in

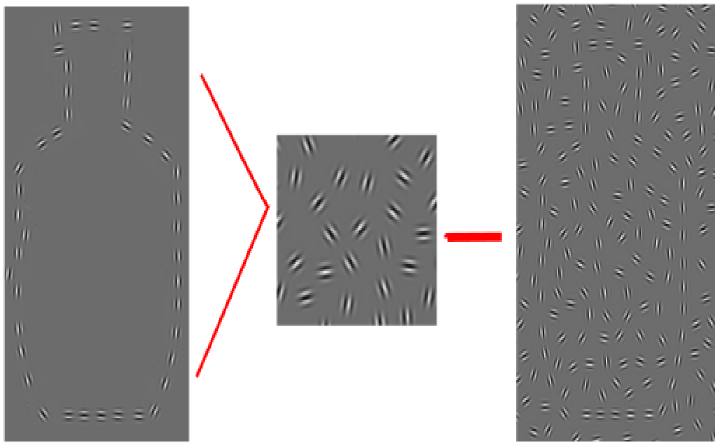

Figure 3.4: **The target region presented to a participant.**
To disrupt the visibility of the target contour the Gaborized contour was presented embedded in a noise field of randomly orientated Gabor patches. The introduction of a Gaborized contour in a randomized noise field presented the possibility that visual differences in the local density of Gabor patches would provide cues to the participant for detection. These local density cues were assessed and removed by determining the pre-set maximum and minimum distances between the noise field Gabor patches that were the least likely to produce local density differences given the set of Gabor patches in the Gaborized contour (Demeyer & Machilsen, 2012).

Figure 3.5.

There were four specific experimental conditions for which the detectability of a target contour was tested: (1) the control condition in which the target was presented alone; (2) the same condition in which the shape of a target was paired with the shapes of the two flanking contours; (3) The different same condition presented the target flanked by two contours of a different shape than that of the target, but same each other; and (4) the different non-same condition where the flankers were different in shape to the target and each other. The flankers (when present) were displayed to the left and right of the target such that their centroid aligned with the target centroid, and the horizontal distance between centroids was approximately 4.7 arcdegrees. Examples of these conditions are presented in Figure 3.6.

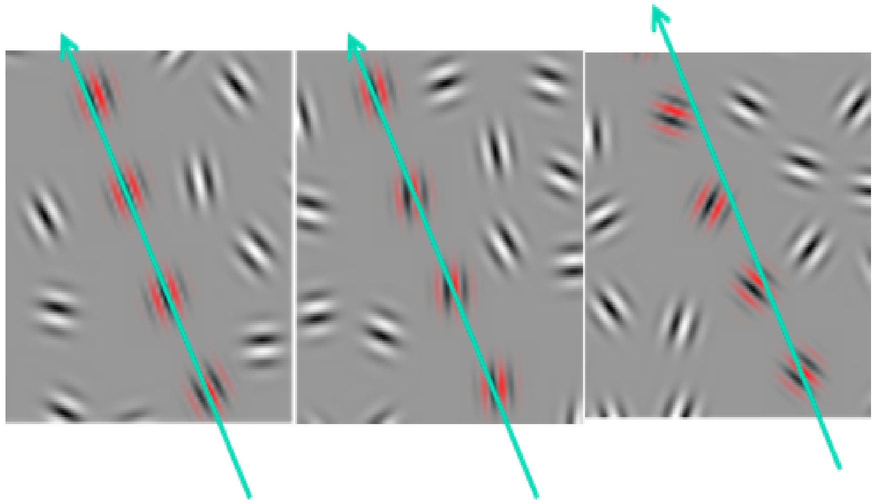

Figure 3.5: **The experimental measurement of orientation noise.** To disrupt the visibility of the Gaborized contour in the noise field, orientation jitter was added to the Gabor patches aligned with the initial shape of the contour. This orientation noise was defined by a magnitude of the random orientation jitter that was added to the individual Gabor patches. The larger the magnitude, the greater the likelihood that the Gaborized contour was indistinguishable from the noise field in which it was embedded. Presented here is a Gabor contour (coloured red for demonstrative purposes, the directionality of the contour is presented as a turquoise line) in a noise field at 0 degrees (aligned with initial shape of contour), 30 degrees (roughly aligned with deviations of maximum +-15 degrees from the initial shape of the contour) and 60 degrees (low alignment of initial shape of contour with deviations of maximum +-30 degrees). 0 degrees corresponds to highly visible target contours and 180 degrees corresponds with a set of Gabor patches indistinguishable from the randomized contour.

3.3.2 Procedure

Each trial consisted of stimulus, a sequential presentation of a target-present panel and a target-absent panel. In the target-present panel the target was displayed centered horizontally. The target absent panel was identical to the target present panel except that there was no target contour present.

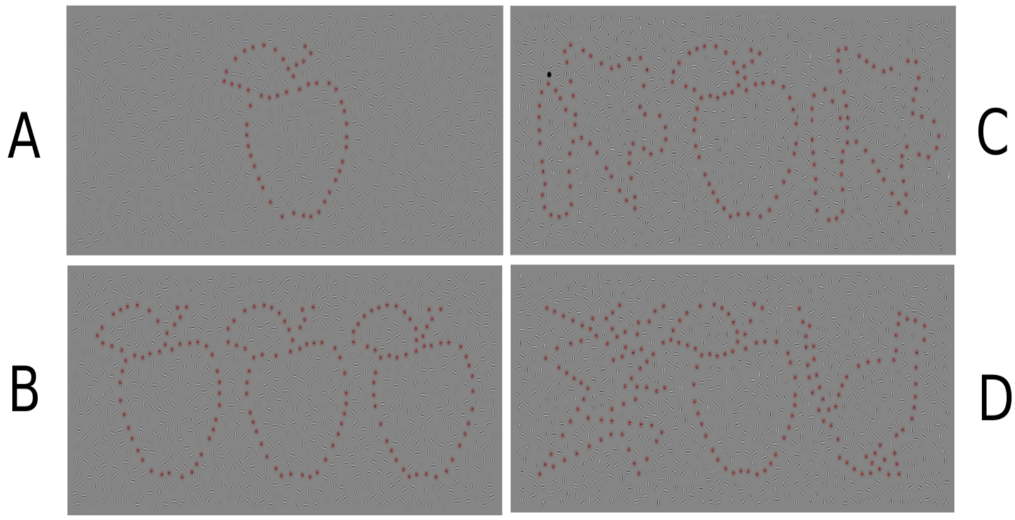

Figure 3.6: **Conditions presented to participant in experiment 1.** In these examples the embedded contours are defined by a set of collinear Gabor patches aligned to a generating shape with a set of randomised Gabor patches both in and without the contour perimeter. Four conditions were presented in the experiment. The (A) control condition, in which a target contour was presented alone, (B) same condition, where the target is presented with two flanking contours of the same shape (C) different matching condition, where the flankers have a different shape that the target contour (D) different non-matching condition, where a target contour is presented two flanking contours, none of which are the same shape.

In order to prevent any gross differences in perceived density of the two types of panels, the average density of the target absent panels was generated by making them the same as the value of the target present condition. The number of Gabor patches in the target-present and target-absent panels was therefore the same.

The density value was further used to create a set of 5 inter-trial display panels for each trial. These inter-trial display panels contained no contour information as they contained randomly positioned and orientated Gabor patches only.

The sequence of stimulus presentation (Figure 3.7) involved an initial fixation cross at the center of the main display panel (750 ms), followed by a fixation cross ap-

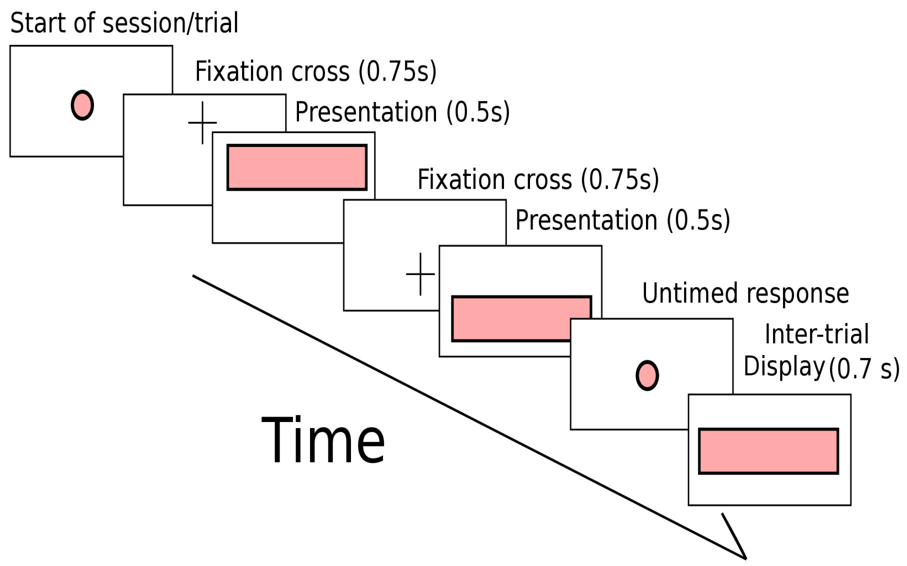

Figure 3.7: **The time course of a single trial**

The stimuli set consisted of two stimuli, either a target-absent or a target-present image one of which contained the target object and one without. Each presentation consisted of an initial fixation cross that directed the observer's attention to the target location, this was followed by one of the stimuli. The stimuli was presented on the right hand side (red) and then on the left hand side (yellow) on screen. Once the two stimuli were presented, a red circle appeared that prompted the subject to indicate in which stimulus (first or second) they saw a target object, this circle remained until the observer made a response. Finally, an inter-trial display was presented.

pearing at the upper or lower half of the overall panel. This was followed by the presentation of either a target-present or target absent stimulus panel for 500 ms. After this time, a fixation cross appeared at the opposite location (lower or upper panel) and was followed by either the target-absent or target-present panel (depending on what was previously shown). After 500ms a circle was presented at the center of the display with no fixed duration in which the participant was asked to respond if a contour was present in either the upper or lower panel. Once a response was recorded, an inter-trial display was presented for 700ms and a central red circle was displayed (200ms) to indicate the beginning of a new trial.

The initial target-present panel consisted of Gabor gratings aligned to the underlying generating shape. The degree of orientational noise jitter was varied according to participant responses using a 1-up 1-down staircase procedure. The initial level of noise jitter for each staircase was at 12 degrees of noise. That is, the contour was extremely visible and detectable to all participants.

The step size down in the initial 3 trials was 16 degrees of noise. This was intended on reducing the number of steps required before the target contour became difficult to detect, if the participant was incorrect at the lowest level of noise, the level of noise remained the same during the first three trials. After the first 3 trials 4 degrees of noise were added if the participant was correct and decreased by 4 degrees of noise if the participant was incorrect.

To extract the detection threshold, the staircase procedure varied the magnitude of the added orientational noise jitter until the participant was no longer able to detect the shape. Each staircase was terminated after 50 trials and the threshold was calculated by taking the mean value over which the last 10 reversals took place.

Here the detection thresholds are presented as the reciprocal detectability values corresponding to the absolute magnitude of orientation noise jitter added per trial. Therefore a decrease in the detection threshold corresponds to a greater degree of orientation noise, and a greater corresponding detectability value.

Data analysis

The detectability of the target-contour was analysed by taking the mean of the detection thresholds for all the target contours under a single condition and computing an ANOVA. Individual subject performance and mean performance across all subjects for an individual target contours were compared to investigate the generality of the results. This involved taking the ratio of the detection threshold for each condition relative to the corresponding value of the control condition (Equation 3.1).

This diagnostic was used to assess the generality of the result, as the overall pattern of the results should reflect the general pattern of the combined results if the experiment is performed as expected. Finally, the data of the individual target contours was compared by ad-hoc groupings to investigate any consistent patterns in the data.

$$N = F/C \tag{3.1}$$

Where N is the magnitude of the detectability results in the presence of flanking contours relative to the control or baseline detection. F is the detection threshold for each conditions, and C is the detection threshold for the control condition.

3.3.3 Results

In order to determine if there was an overall effect of the presence of flankers on contour detectability, the mean detection threshold for each stimulus condition (control, same, different matching and different non-matching) was determined by averaging over all target contour shapes tested for each condition for each participant. The mean values averaging across all participant are shown in the bar plot in Figure 3.8. The results indicated that the most detectable target contours (lowest detection thresholds) were in the condition where the target contour was flanked by contours with the same shape.

An one-way ANOVA with stimulus condition as the factor indicated that there was a statistically significant difference in the detection thresholds ($F(3, 33) = 4.72$, $p < 0.001$). Moreover, planned pairwise comparisons using a Tukey test revealed that the difference between the same condition was significantly different from the control (no flanker) ($p=0.02$) and different matching condition ($p = 0.002$). However, there was no significance difference in either the different matching ($p = 0.92$) or non-matching conditions ($p=0.90$) when compared with the control condition or with each other ($p=0.54$).

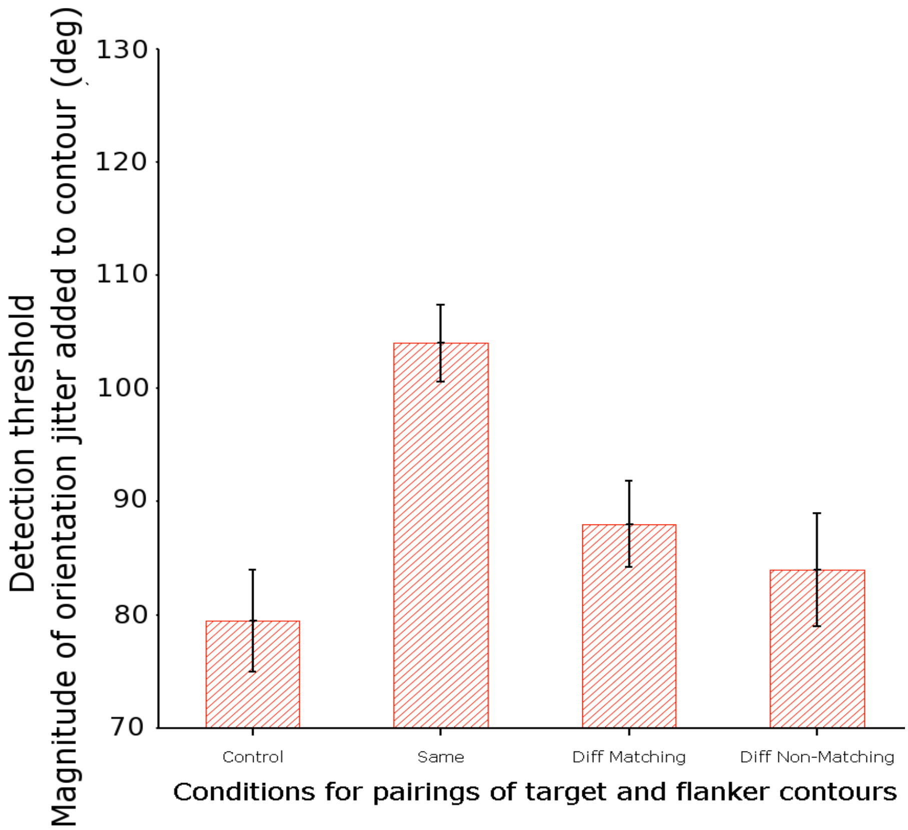

Figure 3.8: **The mean detection threshold of the target contour as a function of each experimental condition.**
The detection thresholds (y-axis) are presented for each of the target-flanker conditions (x-axis). The plotted conditions are the control condition (no flanker surrounding target); same condition (target and flanker share the same shape); different matching condition (target and flanker have a different shape); and different non-matching condition (the target and flankers all have different shapes). The plotted data are the magnitude of orientation jitter added to a central target contour at a detection threshold of approximately 50 percent correct averaged over all participants (n=12). Error bars represent the standard error of the mean.

The data was tested for normality and homogeneity of the variance. A Levene's Test for the equality of variance demonstrated that the homogeneity of the variance was equivalent for each condition ($W = 1.9589$, $p = 0.119$). With Shapiro-wilk tests indicated that the control ($W=0.9899$, $p=0.39$), same ($W=0.9844$, $p = 0.1$), difference matching ($W=0.9822$, $p = 0.06$), and difference non-matching ($W=0.9935$,

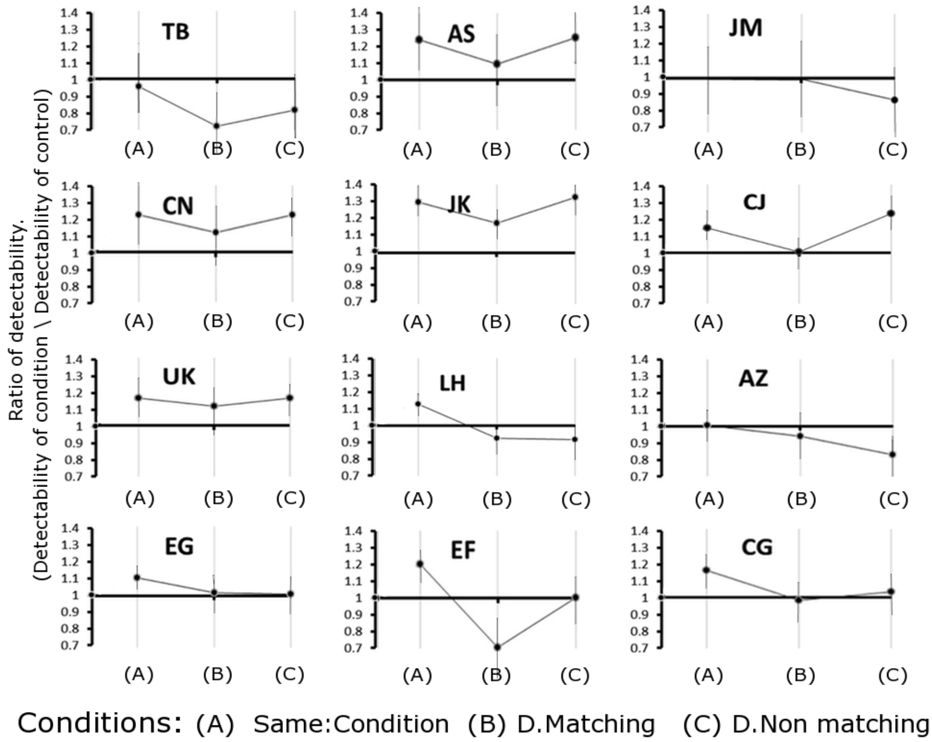

Figure 3.9: **The ratio of detectability of the target contour as a function of each flanking condition for each participant.**

The detectability ratios (y-axis) are presented in which the detection performance for each participant in each condition (x-axis) and is divided by the detection performance in the control. The plotted conditions are the same:control condition, different matching and different non-matching. The trends were not treated as data but rather a guide to plausible trends to be investigated in further experimentation. Error bars represent the standard error of the ratio of the control and flanker condition means.

p=0.76) satisfied normality. A subsequent Q-Q plot confirmed that this was the case though a small number of outliers were present at either end of the plot.

In order to examine individual variations among participants and also among target shapes, the individual results were plotted as a detectability ratio which involved taking the ratio of the measure of detectability for each experimental (flanker) condition relative to the detectability measured in the control (no-flanker) condition

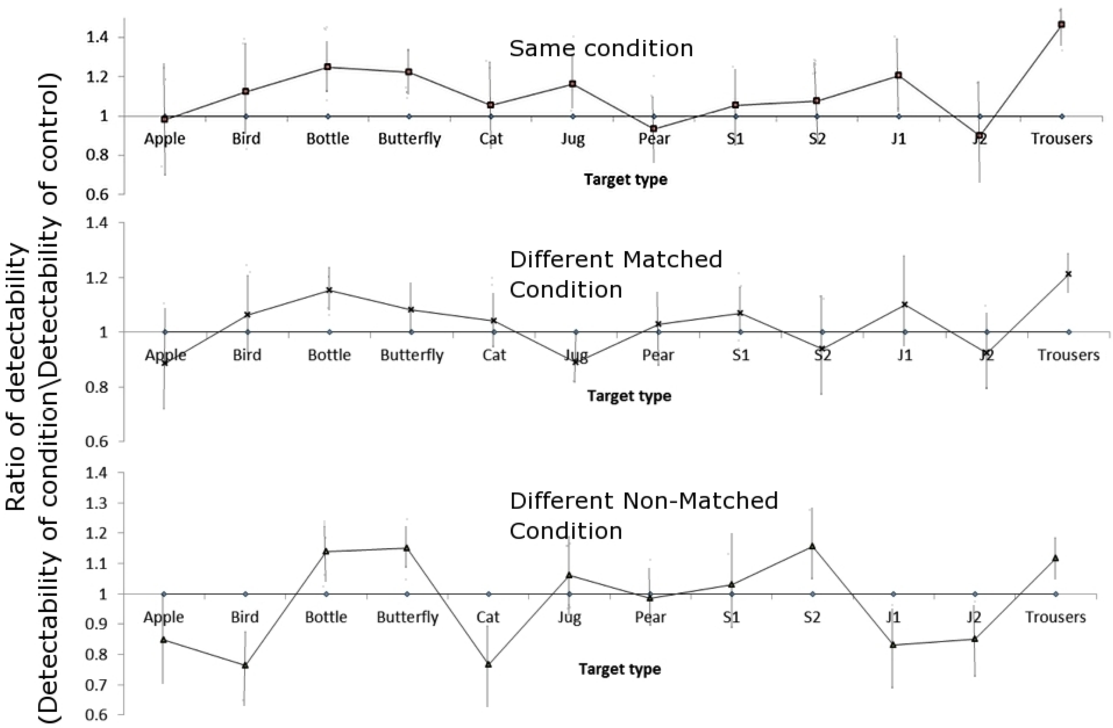

Figure 3.10: **The ratio of the detection threshold as a function of the target contour shape.**

The detection threshold ratios (y-axis) are presented in which the detection performance for each target contour shape (x-axis) is divided by the detection performance in the control. The plotted conditions are the same:control condition, different matching and different non-matching. The trends were not treated as data but rather a guide to plausible trends to be investigated in further experimentation. Error bars represent the standard error of the ratio of the control and flanker condition means.

(equation 3.1). Figure 3.9 shows the detectability ratios for each of the subjects tested. It is clear from the figure that the flanker facilitation effect for the same condition was observed for 9 out of the 12 participants, suggesting the effect was indeed a general one. Both the different same and different non-same conditions showed no consistent effect across observers in comparison to the control condition. Specifically, non-systematic suppressive and facilitatory effects for these latter conditions were found. The different matching condition showed clear facilitatory in 4

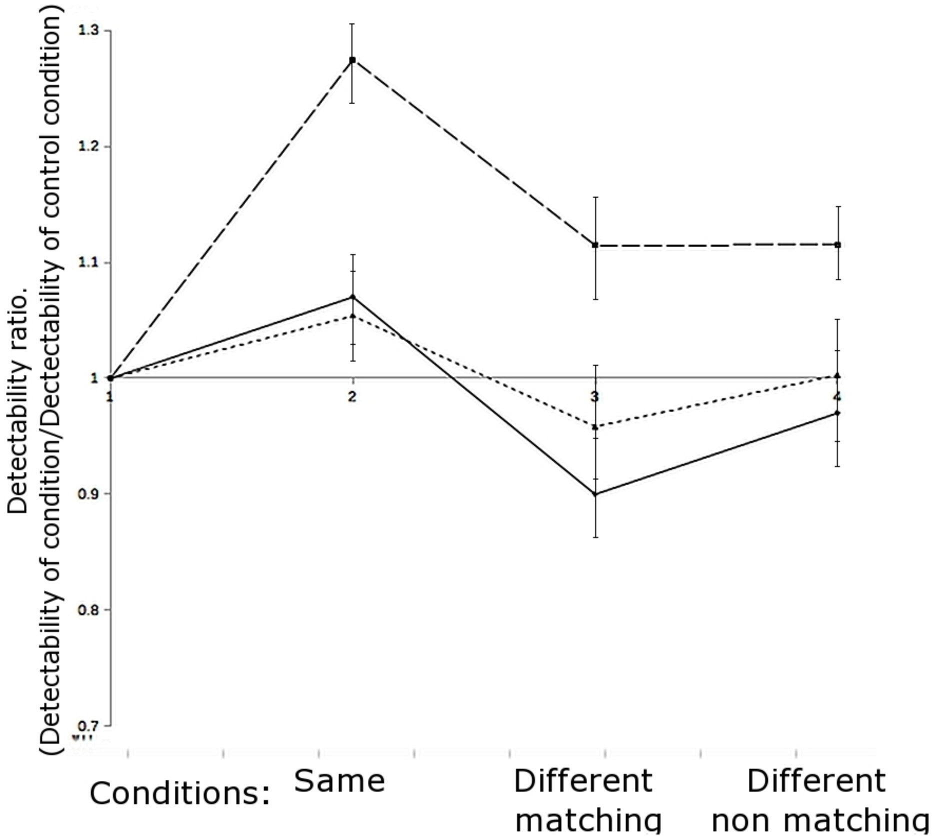

Figure 3.11: **The ratio of the mean detection threshold of the target contour as a function of each condition grouped by general presence of symmetry and familiarity.**

The detection threshold ratios (The relative decrease in contour collinearity between the target contour with and without flankers at the point they were no longer perceived) are presented as groupings of shapes that are generally similar along two dimensions – symmetry and familiarity. The symmetric and familiar group consisted of the Bottle, Butterfly and Trousers shapes (shown as the thick broken line). The asymmetric and familiar group consisted of the Jug, Apple, Bird, Cat and Pear shapes (shown as the solid black line). Finally, the asymmetric and unfamiliar group consisted of the remaining shapes, S1, S2, J1 and J2 (shown as the thin broken line). The trends were not treated as data but rather a guide to plausible trends to be investigated in further experimentation. Error bars represent the standard error of the ratio of the control and flanker condition means.

cases (AS, JK, CN and UK), negligible effects for 4 cases (EG, JM, CJ, and CG) and suppressive effects in 5 cases (TB, AZ, LH, EF and AZ). The Different non-same condition showed facilitatory effects in 5 cases (CN, UK, AS, JK, and CJ), negligible effects in 3 (EG, EF, and CG) and suppressive effects in 4 cases (TB, LH, AZ, and JM).

Detectability ratios for each shape and each experimental condition tested are shown in Figure 3.10. Again, it is clear that, for most shapes tested, there was a clear facilitatory effect in the same condition. Some evidence for facilitation in the different matching condition was also observed for some shapes, particularly those that also showed clear facilitation in the same condition. However, the results for the different non-matching condition were much more variable with seemingly random suppressive and facilitatory effects. Figure 3.11 shows the individual shape data plotted by grouping the shapes tested into three categories based on high-level features that could potentially have contributed to facilitatory or suppressive effect (e.g., familiar, bilaterally symmetric, and geometric shapes). The pattern of the results appeared consistent with these shape groups and may indicate that bilateral symmetry was a significant high-level shape feature that modulated the flanker facilitation effect.

3.3.4 Discussion

The purpose of this first experiment was to investigate whether the addition of flanking contours had a general effect on the detectability of a noisy target contour. Experiment 1 compared the effects of flanker contours on the detectability of a central target contour under a number of conditions in which the congruency of the shapes of the contour pairings (whether the target and flankers were the same or different shapes) was varied. This was done for a set of shapes that contained a number of different shape level features so as to determine if any effect could be associated with the whole configuration of the contour, rather than due to the presence of any specific feature.

The general results of the experiment indicated that when the flankers and the target contour had the same generating shape the detectability of the target contour was increased relative to the control condition. However, a comparison of the performance of the contours relative to the control demonstrated that the presence of symmetry in both the flanker and target contours could be responsible for the facilitation of the detection. It was also shown that facilitation may occur when the target alone is symmetric as the target detectability was greater for such target contours when they were paired with dissimilar flankers in the different matching condition in comparison to the rest of the contours tested.

Previous work has shown that symmetry, in particular bilateral symmetry, facilitated the detectability of target contours under similar conditions involving Gaborized contours disrupted by orientation noise jitter in a 2-AFC style experiment (Machilsen et al., 2009). This may indicate that the perceptual processes underpinning the role of symmetry in the perceptual organisation of Gaborized contours are influenced by additional contour integration in the periphery of a target contour. However, the less symmetric contours may be more difficult to process in the periphery due to more corners/edges being disrupted by the Gabor patches surrounding these extrema. In other words, asymmetric flankers adjacent to the target are less visible than the symmetric stimuli as they are more complex and more subject to disruption from the noise field surrounding the flanking contours.

A secondary methodological concern is that the randomisation of the noise field is based on a standard operation in which uncorrelated white noise is used. This permits the possible spontaneous formation of open contours in the noise field, which, speculatively may provide shape level information for contours with higher frequency spatial information. That is, the more complex contours could be facilitated by the presence of similar information accidentally arising in the control condition due to an inappropriate use of the 1 dimensional noise (Phillips, 2004), in addition to any effect of the presence of flanking contours.

To preclude the possibility of differences in the detectability across the set of target contour in the control condition due to interactions between the complex contours and the noise field, an initial methodological experiment investigates the detectability of a single target contour (Experiment 2a).

3.4 Experiment 2a

The purpose of this experiment is to examine the differential effects of the noise field on the detectability on target contours of varying complexity. To do so, the orientation information in the noise field was adjusted by introducing regions of isolinearly orientated Gabor patches (That is, the orientation of the set of patches was identical).

The extent of the isolinear field was varied with respect to the noise field to determine whether randomised or isolinearly orientated Gabor patches influenced the detectability of the target contour.

3.4.1 Methodology

Participants

20 undergraduate participants performed the experiment and were paid volunteers (13 female, 17 to 30 years). Each participant performed one session of 1 hour. A break was provided mid-way during the session for as long as the participant wished. All observers had normal or corrected-to-normal vision.

Apparatus

The apparatus in experiment 2a was identical with that in experiment 1.

Stimuli

The Gabor patches used had identical parameters to those in experiment 1. To vary the complexity of the target contour, a number of new geometric shapes were created. These shapes are shown in Figure 3.12. These shapes were grouped by increasing

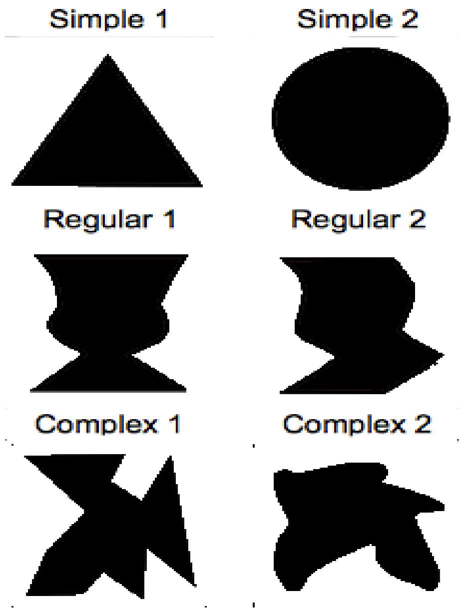

Figure 3.12: **Shapes used to generate target and flanker Gaborized contours in experiment 2a.**
The outlines had three degrees of complexity corresponding to: simple shapes (Top) with low degrees of perimeter variation and high degrees of rotational symmetry, regular shapes (Middle) with a greater degree of perimeter variation and some regularity across the contour and complex shapes (Bottom) with large degrees of perimeter variation and with no regularity across the contour.

numbers of curvature extrema and corners present along the perimeter of shape. The simplest shapes were the canonical shapes of a circle and a triangle. These shapes had the greatest number of symmetries. The second group was generated with more changes in curvature and contained bilateral symmetry, and translational symmetry. The final group consisted of non-symmetric generating shapes with large number of extrema. These groups are shown in Figure 3.12. The experiment consisted of only the control condition from experiment 1. The target contour was presented by itself in four different versions of the noise field,created by changing the proportion of the flanker region containing either an isolinear or randomly distributed noise field (Figure 3.13). The proportions consisted of 100, 70, 35, and 0 percent of the flanker region only (Figure 3.14).

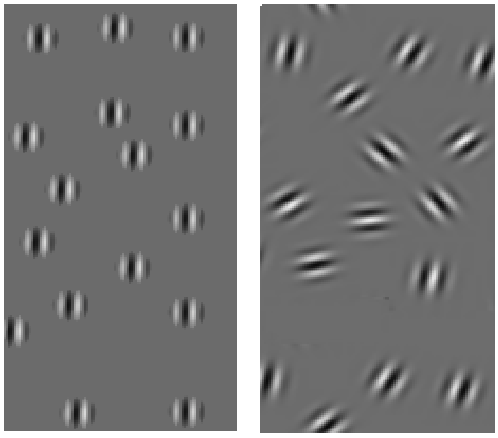

Figure 3.13: **Orientation of Gabor patches in periphery.**

To investigate the use of orientated Gabor patches as a method for increasing the visibility of flanking contours it was necessary to confirm that the use of the different types of Gabor patches were suitable for a control condition. Two types of Gabor fields were selected: (A) an isolinearly orientated field that consisted of randomly arranged Gabor patches with a single orientation and (B) a noise field that consisted of randomly positioned and orientated Gabor gratings.

3.4.2 Procedure

The procedure was identical to that in experiment 1. The participant instructions were adjusted to take into account the difference in stimuli between the two experiments with no reference to the presence of flankers.

3.4.3 Results

In order to determine if the detectability of a central target contour was affected by the noise field in the flanker region, and correspondingly, to determine the validity of the control condition given the premise of the thesis (A central target being sensitive to peripheral shape information) a number of contours of varying complexity were presented with Gabor fields with randomised or isolinear orientation information in the peripheral, flanking region. The mean detection threshold for each stimulus condition (100, 70, 35, and 0 percent of the flanker region covered by an isolinear field) was determined by averaging over all target contour shape groups tested for

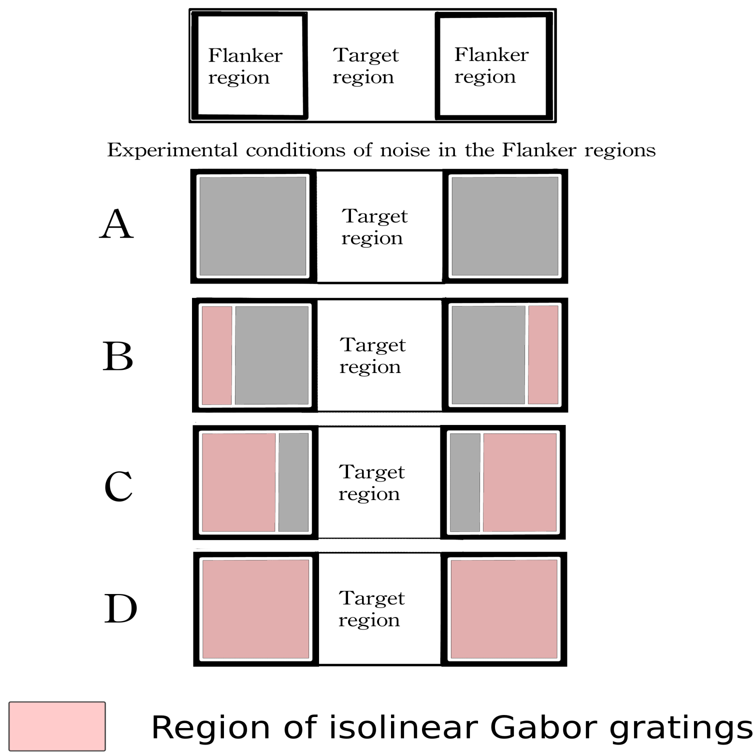

Figure 3.14: **Conditions presented to participants in experiment 2a.** The detectability of a Gaborized contour was investigated when the two flanker regions adjacent to the region containing the target (Upper) contained fields of isolinear (Red) or noisy (Grey) Gabor patches. In each condition both flanker regions had the same noise field distribution relative to the target. That is, each flanker region contained the same proportion of isolinear to noisy gabor patches, and the flanking regions contained either a noise field (Grey); a isolinear field (Red) or both. The conditions presented to participants consisted of isolinear field covering (A) 0, (B) 30, (C) 70 (D) 100 percent of the flanking region.

each condition for each participant.

The mean detection thresholds averaged across all participant are shown in the line plot in Figure 3.15. Overall, there was no systematic enhancement or suppression with increasing the extent of the flanker region covered by a randomised noise field. However, the complex contour group showed a greater level of variability, but

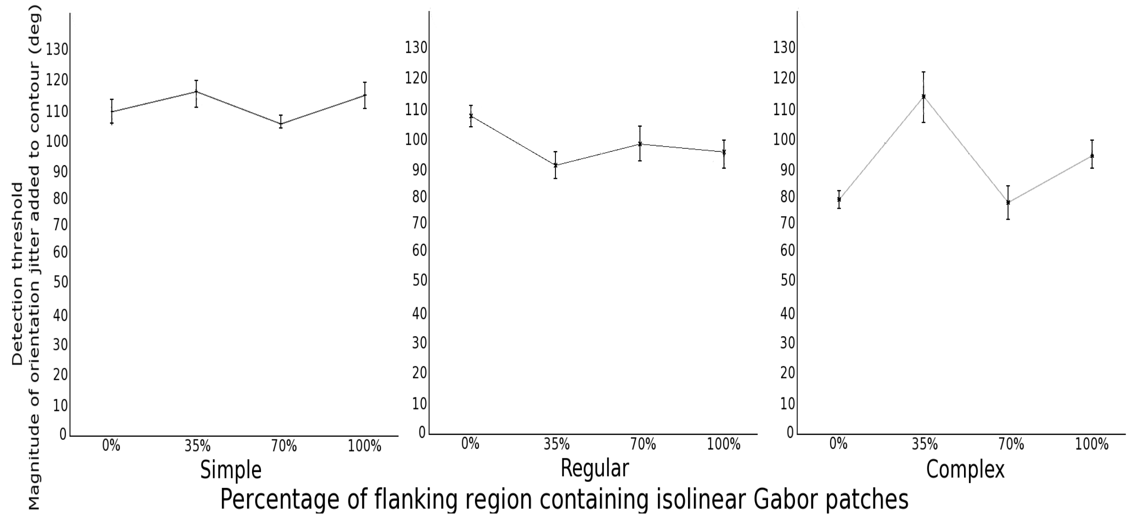

Figure 3.15: **The mean detection thresholds of the target contour as a function of the peripheral Gabor field.**

The detection thresholds (y-axis) are presented for each of the target-flanker conditions (x-axis). The plotted conditions are the detectability of the target contours (simple shapes – black line, regular shapes – dark grey, complex shapes – light grey) with the extent of the flanking region containing isolinearly orientated Gabor patches (0, 35,70 and 100 percent of the flanking region contains Gabor patches that are aligned vertically). The plotted data are the magnitude of orientation jitter added to a central target contour at a detection threshold of approximately 50 percent proportion correct averaged over all participants (n=20). Error bars represent the standard error of the mean.

because neither the enhancement nor suppression were systematic effects, this was discounted. The data was analysed by running one way ANOVA on the individual groups. The results reflected the observations averaged across groups, with no statistically significant differences among the groups of target contours as a function of the extent of the isolinear region averaged over all shapes (simple shapes ($F(3, 57) = 1.77$, $p = 0.159$), regular shapes ($F(3, 57) = 1.38$, $p = 0.26$), and complex shapes ($F(3, 57) = 2.33$, $p = 0.08$)).

3.4.4 Discussion

These results indicate that the detectability of the target control was not affected by the nature of the noise field (either isolinear or randomly orientation Gabor patches) in the flanker region and that this was true for shapes with varying complexity. Detectability of a target contour in randomized noise control appears to be equivalent with either a noise field or isolinear field in the flanker region. An important aspect of this result is while the use of isolinear Gabor fields both in and outside of the boundary of a Gaborized contour have been shown to improve the detectability of a target Gaborized contour (Wagemans & Machilsen, 2010), no long range interaction was observed. Therefore, the results of the experiment indicated that the control conditions involving either a whole noise or isolinear field in the flanking region should be equivalent. As the use of an isolinear field surrounding a flanking contour may increase the detectability of such flankers and the control conditions are comparable, this method (use of isolinear fields in the flanking region) was used to test whether the observed flanker facilitation effect in the first experiment was associated with simply repetition of contours, or the result of specific features in the following experiment.

3.5 Experiment 2b

The first experiment demonstrated that flanking contours facilitated the detectability of a target contour when such flankers were the same generating shape as the target. A number of factors were not taken into account in this initial experiment that were revealed in the more detailed analysis of the data of the first experiment based on properties of the target shapes used (e.g., presence of symmetry). Previous research has indicated that the perceptual organisation of a closed Gaborized contour is sensitive to a number of higher level factors such as the presence of bilateral symmetry (Machilsen et al., 2009); familiarity and predictability with the presented contour (Sassi, Demeyer, & Wagemans, 2014) as well as how identifiable the contour is to the observer (Nygard et al., 2011; Sassi et al., 2012).

The present experiment investigates the role of higher shape level features to the flanker facilitation effect. Two such factors were examined: The presence of bilateral symmetry; and whether the contour was familiar (I.e., the shape was of everyday, familiar objects such as a cat or butterfly). Since these factors are known to affect the detectability of shape, other results from the first experiment may have been moderated by the intrinsic visibility of the flanker contours in the noise field in addition to the nature of the flanker contours themselves. Therefore, in the current experiment, the flanker facilitation effect was tested under condition where the flankers were embedded in either a randomly oriented noise field or an isolinear field (increased visibility).

3.5.1 Methodology

Participants

16 undergraduate participants (17-30 years; 14 female) performed the experiment and were paid volunteers. Each participant performed two sessions of 1 hour. A break was provided mid-way during the session for as long as the participant wished. All observers had normal or corrected-to-normal vision.

Apparatus

The apparatus in experiment 2b was identical to that in experiment 1.

Stimuli

A subset of previously used familiar shapes were used to generate a set of grouped Gaborized target and flanking contours. These shapes were grouped by two factors (bilateral symmetry and type of Gabor field in flanking regions) to create four sets: bilateral contours with isolinear field; bilateral and randomised noise field ; asymmetric and with isolinear field; and asymmetric and randomised noise field. The set of shapes is presented in Figure 3.16 and an example of a contour surrounded by either field is presented in Figure 3.17.

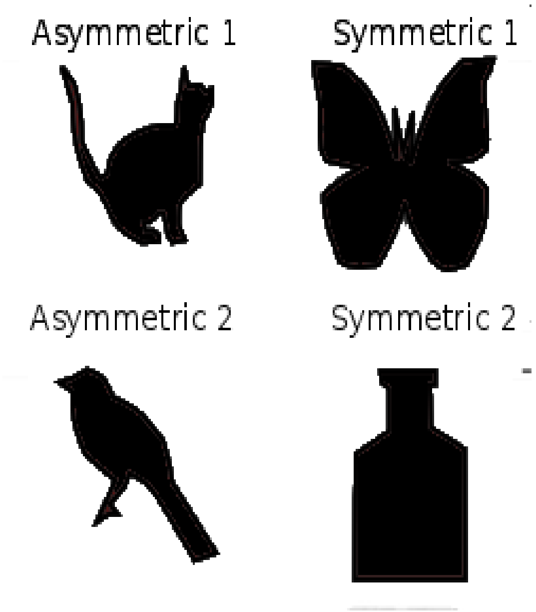

Figure 3.16: **Shapes used to generate target and flanker Gaborized contours in experiment 2b.**

The dataset in experiment 1 and previous research indicated that either symmetry or familiarity may be important to the flanker facilitation effect. To control for familiarity four shapes were chosen from the initial experiment that formed two groups of familiar contours. These two groups were either asymmetric contours or bilaterally symmetric contours.

The contours for each group were presented in a set of three conditions that were created by pairing the target with flanking contours of varying shape. The three conditions were: the control, in which no flankers were presented; the same condition, in which the target and the flankers had the same shape; and different matching flanker, in which the target differed in shape from the two flankers which matched each other.

Procedure

The procedure was identical to that in experiment 1 and presented over two sessions. There were 24 staircases from all conditions. These were divided into 2 sets of 12 staircases. Each session consisted of equal numbers of staircases for each condition. The exact generating shape used for said condition was randomised.

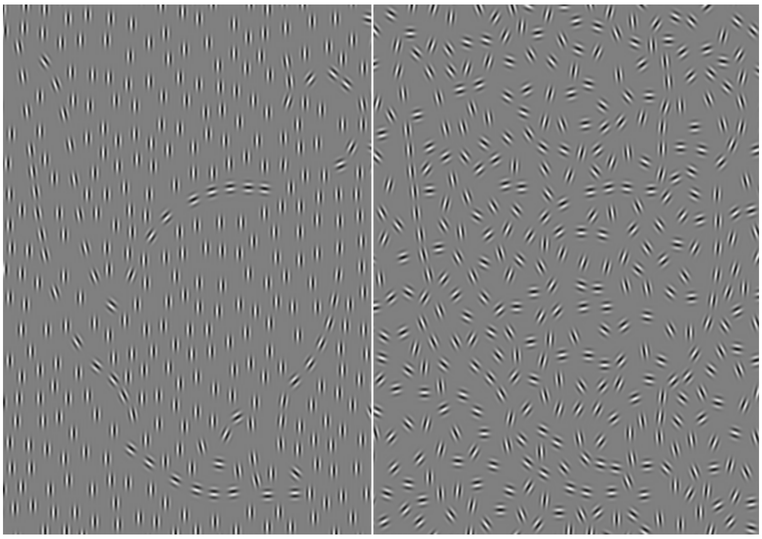

Figure 3.17: **Examples of the flanking contours embedded in the Gabor fields of different types.**
To increase the visibility of the flanker contours and to compare the magnitude of the facilitation caused in less and more visible conditions the area surrounding the flankers was filled with non-overlapping regions of either isolinearly orientated or randomised patches. A cat contour is presented in a field of either (Left) isolinear and (Right) randomly orientated noise fields.

3.5.2 Results

Figure 3.18 (p.93) and 3.19 (p.94) shows the mean detection thresholds for target contours for the three experimental conditions. Figure 3.18 plots the mean detection thresholds for the whole experimental dataset (type of noise and target-flanker condition, symmetry and target-flanker condition). Figure 3.19 plots the mean detection thresholds for the subdata concerning two of the main experimental conditions of particular interest: the target-flanker condition alone and whether the target contours were with or without bilateral symmetry in the target contour. The data was analysed using a factorial 3x2x2 ANOVA, with the main experimental factors being: the presence or absence of flanking contours; the presence of symmetry in the target contour; and the type of noise field in flanking region. Both 2-way and 3-way interactions between these factors were considered.

The purpose of these experiments was two-fold. Firstly, to determine whether the effects observed in experiment 1 could be replicated, and secondly, whether the greater detectability of target contours paired with flankers of the same shape was associated with the presence of a feature (bilateral symmetry) and whether it was sensitive to the visibility of the flanking contours.

A number of results were discernible from the overall data. As with the first experiment, the detectability of a target contour paired with flanking contours with the same shape (same condition) was greater than those of the other conditions. This reflected the main effects observed in the ANOVA with presence of flankers having a significant effect on the mean detection thresholds of the target contour ($F(2, 30)=3.21$, $p < 0.04$). Subsequent planned pair wise comparisons using a Tukey test indicated that the same condition contributed to the significant effect ($p<0.001$).

A number of other main effects were examined including the presence of bilateral symmetry and whether the flanking region containing an isolinear or randomized Gabor field. As with previous research, the overall presence of bilateral symmetry was shown to result in greater levels of detectability for the target contours. This is shown in Figure 3.19. The ANOVA reflected this observation ($F(1, 15)=16.95$, $p<0.001$). Correspondingly, the results of experiment 2a were replicated as no significant effect on differences in the detectability of the target contour was observed when presented with flanking regions of different types of Gabor fields ($F(1, 15) = 3.21$, $p = 0.061$).

To examine whether the flanker facilitation effect was a feature-specific or general perceptual mechanism (e.g., sensitive to the disruption of more complex flanking contours) the detectability for the target-flanker conditions was compared when presented in either the isolinear or noise fields. Shown in Figure 3.18 the overall detectability of the set of target contours was shown to be greater when flankers were surrounded by the isolinear field. Furthermore, the facilitory effects were observed for both the symmetric or asymmetric contours indicating that the flanker facilitation was a general perceptual mechanism. The 3-way ANOVA ruled out this effect being associated with either a 3-way interaction ($F(11, 30)=21.65$, $p = 0.78$); or two way interactions between either presence of symmetry and noise/isolinear field ($F(3, 15)=5.35$, $p = 0.78$); or the presence of symmetry and condition ($F(5, 32)=14.35$, $p = 0.055$).

The remaining interaction between the condition of the target and flanker and the type of Gabor field was shown to be significant corresponding to the expected results ($F(5, 30)=5.86$, $p < 0.05$). Pair-wise turkey tests indicated that the specific interaction of isolinear field in the same ($p<0.01$) and different same ($p<0.01$) conditions were significant with respect to the control and not with each other ($p = 0.54$). However, such a pattern of results is also consistent with another interpretation arising due to a confound in which the presence of a noise field in the control condition facilitates the target contour when the generating shape is recognisable. This will be discussed in the next section in more detail.

3.6 General Discussion

The present set of experiments was designed to examine whether the detectability of a Gaborized contour was affected by the presence of flanker contours with similar or dissimilar shape. These flanking contours were located laterally with respect to the target contour; and equidistant on the left and right sides of the target contour. An important theoretical component to these experiments that distinguish them from previous examples of behavioral enhancements associated with multiple flanking objects was that the detectability of the contour was a function of the successful local grouping processes. That is, to detect a Gaborized contour the local orientations of a set of Gabor patches needed to be interpreted as belonging to a single contour.

The findings of the initial study demonstrated that the presentation of flankers with the same generating shape as the target contour facilitated the detection of target contours (Experiment 1). A number of differential effects were observed in experiment 1 in which stimuli containing symmetries showed a greater degree of facilitation across the conditions. However, a number of factors could explain the apparent connection between the presence of symmetry and the modulation due to the presence of shape-level flankers.

The asymmetric stimuli may have been intrinsically more difficult for the visual system to integrate in a noise background due to the relative complexity of contours. For example, a cat is a more complex shape than either the butterfly or trousers (which are bilaterally symmetric). Alternatively, the presence of symmetry may have been involved indirectly in the facilitation by making the flankers more visible. A third outlying possibility was that the effect of peripheral shape information was linked to the spontaneous formation of contours in the noise background.

Experiment 2a tested whether the noise field in the flanker region contributed to target detectability in comparison with isolinearly orientated Gabor patches. No systematic effect of the presence of regions of noise on the detectability of target contours of multiple complexity was observed. In conjunction with previous research, which demonstrated that the presence of different types of noise fields (randomised, orientated, etc) influenced the detectability of a target contour (Wagemans & Machilsen, 2010), this experiment indicated that the detectability of a target contour was a suitable control condition for further research.

Experiment 2b compared a subset of two groups of recognisable contours with and without symmetry under the same conditions as experiment 1. Additionally, a second factor - whether the field around the flanker was random noise or isolinearly orientated - was compared across the conditions. Importantly, the results indicated that when the type of field around the flanker region was isolinearly orientated the flanker facilitation effect (in the presence of same-shaped flankers) occurred for both sets of contours regardless of the presence of symmetry. This suggests that symmetry may have been having an indirect effect on facilitation by making the flanker contours more visible.

This set of experiments has demonstrated a novel effect in which the contour integration of a closed target contour is facilitated by the presence of flanking contours of the same shape. Similar effects have been observed in which the presence of a single higher level feature associated with a contour, such as familiarity or how identifiable it is to an observer, has been shown to be aid in the integration of target contours (Sassi et al., 2014; Nygard et al., 2011; Sassi et al., 2012). More directly related to the duplication of shape level information, Stojanoski and Niemeier (2012) have shown that feature based attention enhanced the detection of peripheral flanking contours when they share a specific feature with a central, attended target. Interestingly, this process occurred only when the task conditions were more difficult (I.e., the detection threshold for the detection of the flanking contour was lower [75 percent detectability] than that of a second easy condition [95 percent detectability]).

These experimental findings may therefore represent an interesting and unintended demonstration of the consequences of feature based attention. In such a model, attending to a central target task that shares features with the surrounding flankers enables greater access to the shape information present in the flankers. In turn, the visual system integrates this additional organizational information into the contour integration processing that occurs in the central region. Further research is required to determine if this is the case.

One issue with the findings is whether the experimental evidence conclusively demonstrates that the flanker facilitation effect is a general effect occurring with all contours or a subset associated with symmetric features. The field of isolinearly orientated Gabor patches was intended to take into account the differential effects of using flanking contours of varying complexities. However, there are two possible interpretations that prevent a conclusive decision about the effect.

The pattern of results could have arisen due to an increase in the visibility of the flanker contours, or alternatively, because the presentation of a noise field contributes to the detectability of the target contour when the target contour is familiar to the observer, due to the formation of spurious contours in the flanking regions contributing accidentally to a lateral enhancement. In part, this may explain why there was no effect on detectability in experiment 2a. That is, that any contributing factor associated with the noise field was linked to a familiarity with the target contour. The motivation for this second explanation is that textural information (Landy & Bergen, 1991; Julez, 1981) is an important factor in perception and may have influenced the detection of familiar contours due to some unknown perceptual interaction.

A number of other methodological issues may have influenced the results. For instance, the participants may have been overtly attending to, or looking at the flankers. The presentation of the panels containing the target and flankers were for a duration of 500ms, however, saccades can occur in 150 to 200ms (Rolfs, 2009), which would permit at most 1 to 2 saccades. This was discounted as being less likely as participants were explicitly told to both ignore any peripheral information and focus only on the target region, and look specifically in the region around the fixation cross.

In addition, the randomization of both the target presentation and the staircases would require the participants to perform such a strategy efficiently and consistently across all targets and target conditions for over an hour as, in particular with the first experiment, all participants except for three showed the pattern of results.

Although an argument can be made that as bilateral symmetry takes less time to perceptually process, recent work measuring contour integration in the periphery has shown that bilateral symmetry does not appear to aid the detection of Gaborized contours outside the fovea (Sassi et al., 2014). If participants did pursue this strategy, viewing the flanker directly could induce a foveal template (Desimone & Duncan, 1995; Bundesen, Habekost, & Kyllingsbaek, 2005; Tünnermann, Born, & Mertsching, 2013; Olivers, Peters, Houtkamp, & Roelfsema, 2011) that could enable contour integration in the noisy central target when refixation occurs. In this case, it would be expected that the facilitation observed would occur in the same condition (as the data confirms).

However, a corresponding suppression of the detectability of the target contour would be expected when the flanker template contrasts with the noisy target (different conditions). However, no systematic suppressive effects were observed and in particular, experiment 2b demonstrated that the facilitation due to the presence of flankers may occur due to the presence of the process of contour integration per se (e.g., a reduction of facilitation when spurious contour formation was controlled for was found; facilitation was found to occur at equivalent levels in both the same and different conditions when visibility of the contour was improved by using a isolinear field).

There were 3 participants in Experiment 1 who showed different results than the remaining 9. In these cases the same condition showed no additional facilitation while the different same and different non-same conditions showed small suppressive effects that would be consisted with strategies described earlier (foveating the flankers).

This pattern of response is more consistent with looking back and forth at the flankers as it should balance any facilitory effect of same flankers (good template but short integration time in the same condition; bad template but short integration time for different conditions). For these reasons it was considered likely that the results did indeed indicate a perceptual effect in which flankers facilitated the target contour. Though, on the basis of the present experimental conditions it was not clear what factors were the precise determinants that caused the effect.

3.7 Conclusion

Using a simple psychophysical task it was demonstrated that additional information in the form of flanking contours played a role in the detection of a target-contour from a background of noisy Gabor Patches. The findings suggest that repeated shape information in the visual field is useful for the perceptual process of contour integration. However, this process may involve local correlations across the visual field, or the presence of important shape features such as bilateral symmetry and recognisability.

A large number of studies have shown that flanker facilitation occurs for local orientation features (see General introduction) however, to the authors knowledge, this is the first evidence that demonstrates a type of facilitation on the detectability of Gaborized contour associated with shape-level information presented in the surrounding flanking region. The relevant shape information - curvature, spatial angles, area enclosed by a shape, symmetry, familiarity - may be more fully integrated across the visual field than studies which explicitly focusing on local and mid-level factors have previously demonstrated.

This set of experiment raises a number of questions: Is the contribution to contour integration from the flanking region due to the presence of contours per se, or rather a shape-level process that involves the correlations between the central foveal region and the periphery? Is familiarity with the contour (and therefore memory encoding) required for the perceptual process to function? Is the observed process a simple gain caused by the presence of certain features or does the strength of the effect depend on what and where additional information is provided in the visual field? Does the perceptual process represent a modulation of the capacity to separate figure from ground, or is it tied to local grouping of contrast features? And do any more general shape properties such as the aspect ratio or the compactness determine how the shape level flanker facilitation process occurs.

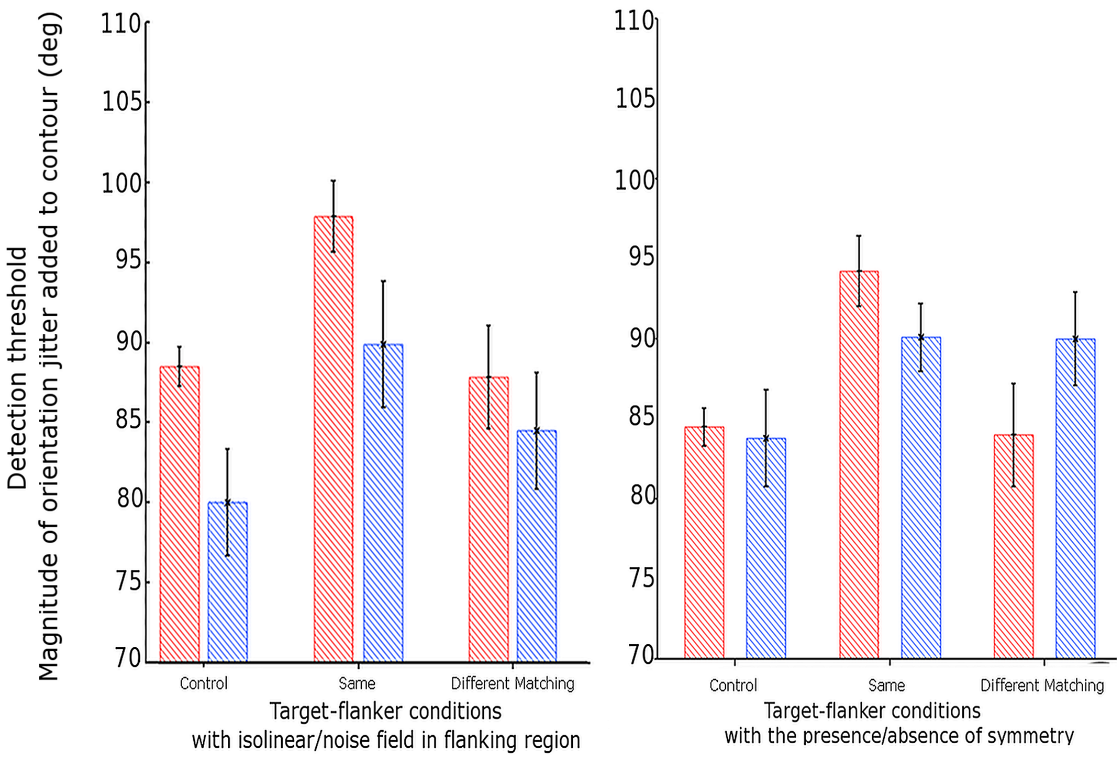

Figure 3.18: **The mean detection threshold of the target contour as a function of the main experimental interactions (noise and target-flanker, symmetry and target-flanker conditions).**

The mean detection thresholds (y-axis) of the target contour for each experimental condition in the experiment (x-axis). The detectability thresholds are presented for each of the target-flanker conditions. The plotted conditions are: (Left) The presence (red bar) or absence (blue bar) of an isolinearly orientated Gabor patches in the flanking region with the target/flankers in the control condition (no flanker surrounding target); same condition (target and flanker share the same shape); and different matching condition (target and flanker have a different shape). (Right) The presence (red bar) or absence (blue bar) of bilateral symmetry with the target/flankers in the control condition (no flanker surrounding target); same condition (target and flanker share the same shape); and different matching condition (target and flanker have a different shape). The plotted data are the magnitude of orientation jitter added to a central target contour at a detection threshold of approximately 50 percent proportion correct averaged over all participants (n=16). Error bars represent the standard error of the mean.

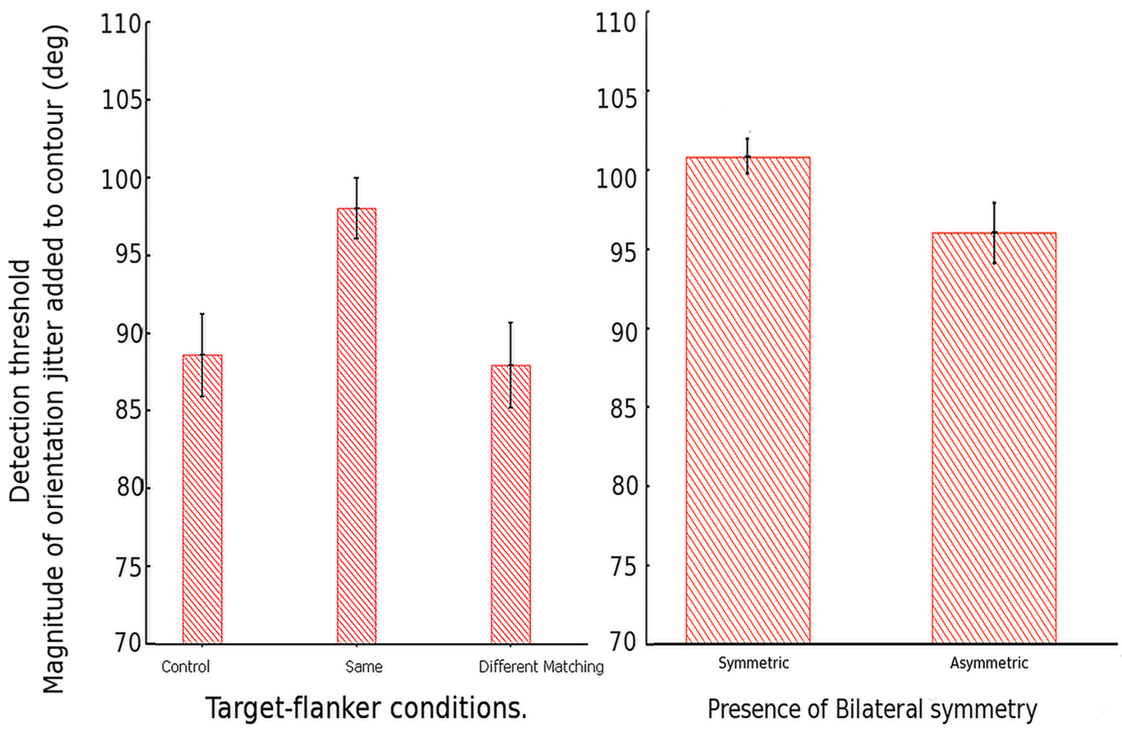

Figure 3.19: **The mean detection thresholds of the target contour of the main conditions (symmetry and target-flanker)**

The mean detection threshold of the target contour (y-axis) for each experimental condition in the experiment (x-axis). The detection thresholds are presented for each of the target-flanker conditions. The plotted conditions are the (Left) control condition (no flanker surrounding target); same condition (target and flanker share the same shape); and different matching condition (target and flanker have a different shape) for all contours used in experiment. (Right) The presence or absence of bilateral symmetry with the target/flankers presented to the participant. The plotted data are the magnitude of orientation jitter added to a central target contour at a detection threshold of approximately 50 percent proportion correct averaged over all participants (n=16). Error bars represent the standard error of the mean.

Chapter 4

Contour integration is facilitated by the presence of adjacent contours that share shape-level features.

4.1 Abstract

The detection, recognition and encoding of object shapes is a complex process that involves the spatial integration of low-level features such as contrast and orientation. However, high-level features, such as bilateral symmetry and shape familiarity are known to affect visual mechanisms underlying shape detection. In a previous study, the detection of a target Gaborized contour (with detection dependent on successful contour integration) was facilitated by the presence of flanking contours of the same shape as the target. The present study investigated the role of high level information (bilateral symmetry, shape familiarity) on this flanker facilitation effect. Detection of Gaborized contours was tested for four different sets of 2D shapes. These sets were based on the presence or absence of high level features (symmetry, familiarity). Shape detection (contour integration) thresholds were measured using a 2-AFC adaptive staircase procedure in which orientation noise was added to the Gaborized contour until participants were unable to detect the target contour. Consistent with results from the previous study, the detectability of a target contour was facilitated by the presence of flanker contours with same shape as the target, in contrast to the other condition where the target was presented alone or with a different flanking shape. Analysis revealed a role of symmetry as an independent shape level feature in this flanker facilitation effect. Specifically, a greater magnitude of facilitation was observed when the target and flankers contained bilateral symmetry even in cases where the target and flanker shapes were different. Further analysis of the complexity of target and flanker shapes determined that the detection performance and subsequent shape level facilitation was consistent with a probabilistic perceptual process extracting a smooth contour from the local orientations present in the noise field on the basis of shared global features.

4.2 Introduction

When detecting the presence of an object in the environment, the visual system is presented simultaneously with many potential sources of information. Some of this information is highly localised, with a large amount of different features (such as localised contrast, orientation, etc.) (Wallach, 1935; Attneave, 1954), while other visual regularities, such as symmetry, are distributed across the visual field (Attneave, 1954; Wagemans, 1995). For instance, at a local level, seminal research by Hubel and Wiesel (1962, 1968) showed that individual cells in the v1 region of the visual system were specifically tuned to the most basic visual features, such as luminance, contrast and orientation, required for the detection of elements of shape contours. The visual system has been shown to integrate and group such local features together in a process known as contour integration (Wertheimer, 1923; Gilbert & Wiesel, 1979, 1983; Field et al., 1993; Barlow & Reeves, 1979; J. Beck et al., 1989; Smits et al., 1985; Loffler, 2008).

This perceptual activity is known to be sensitive to the curvature of contours that arise from the spatial relationships of the orientation and contrast that make them up (Blakemore & Over, 1974; Watt & Andrews, 1982; Hoffman & Richards, 1984) and that behavioural experiments has identified the convexity of curvature as being an important psychophysical cue (Bertamini & Wagemans, 2013). While such processes are hierarchical - with low-level processes leading to the formation of shape level regularities - the visual system can often demonstrate sensitivity to global features that cannot be explained by simple local feed-forward processing alone. One example of non-linear higher level sensitivity is connected with the characteristic attribute of the delineating boundaries of real objects. This property, known as contour closure, has been shown to be a critical factor in the process of contour integration (Elder & Zucker, 1993; Kovacs & Julesz, 1993; Gerhardstein et al., 2012).

Other such regularities are known to be psychophysically relevant to the detection of objects. In particular, the shape aspect ratio (Zusne & Michels, 1962a, 1962b; Regan & Hamstra, 1992); shape circularity/compactness (Zusne & Michels, 1962b; Gallant et al., 1993, 1996; Wilkinson et al., 2000; Wilson & Wilkinson, 1998; Dumoulin & Hess, 2007); how an object's parts relate to each other (the configuration of an object) (Rensink et al., 1997; Bertamini & Farrant, 2005; Hoffman & Singh, 1997; Keane et al., 2003); and viewpoint (Tarr & Pinker, 1989; Jolicoeur & Milliken, 1989; Moses et al., 1996; Vetter & Poggio, 1994; Palmer et al., 1981; Vetter & Poggio, 1994; Koenderink & Van doorn, 1979; Tarr & Kriegman, 2001) have all been shown to be important for the performance of detection tasks in behavioural experiments.

4.2.1 The detection of symmetry and its effect on the detectability of a Gaborised contour.

One specific feature that is readily detectable in its own right is symmetry. Symmetry has been shown to play an important role in a number of shape detection tasks (Mach, 1885/1959; Attneave, 1954; Delius & Nowak, 1982; Bornstein et al., 1981; Wagemans, 1995; Treder et al., 2011; de Kuijer et al., 2004; van der Helm & Leeuwenberg, 1996, 2004; Treder, 2010; Friedenberg, 2000; Baylis & Driver, 2001; Machilsen et al., 2009). Symmetry arises due to the presence of localised regularities that can be globally mapped onto one another, it can therefore occur due to the spatial context of objects in a scene. For instance, the alignment of the two edges of two objects that contain the same or inverted curvature can create inter-object symmetries. Such inter-object symmetries have been linked to the detection of multiple objects in a scene (Koning & Wagemans, 2009; Baylis & Driver, 1995, 2001; van der Helm & Treder, 2009; Bertamini, 2010).

Recently, the presence of symmetry has been shown to play an active facilitatory role in low level perceptual organisation. In particular, Machilsen, Pauwels and Wagemans (2009) used a simple detection task based on the successful contour integration of a Gaborized contour to examine whether bilateral symmetry influenced how the visual system organised local Gabor patches into a coherent contour. They found that symmetries permitted lower overall detection thresholds, showing indirectly that such shape level features can modulate the local processing of an attended target. However, in a follow up study involving eye-tracking it was demonstrated that the enhancement to the contour integration of a target contour was limited, and such effects could not be observed in the peripheral regions of the vision field (Sassi et al., 2014).

These findings indicate that the global shape of an object and the subsequent shape level features (e.g., bilateral symmetry, aspect ratio) are integral to the early levels of visual processing. Other higher level cognitive factors, such as the ability to recognise a shape have also been shown to play a role in the processing of local features.

4.2.2 The effect of familiarity on the perceptual organisation of Gaborized contours.

A person′s ability to recognise an object is a complicated perceptual process − in some cases a person can remember a single object in a few seconds, in other cases, for example in the presence of visual noise, it requires longer periods of exposure or constant repetition before a person becomes familiar with the features and the object being seen. One important aspect of this process is that the visual system is known to encode certain important viewpoints of a single object rather than every conceivable set of viewpoints that the object encompasses (Tarr & Pinker, 1989; Jolicoeur & Milliken, 1989; Moses et al., 1996; Vetter & Poggio, 1994; Palmer et al., 1981; Vetter & Poggio, 1994; Koenderink & Van doorn, 1979; Tarr & Kriegman, 2001).

Familiarity with an object has been shown to influence how readily an observer sees and organises the contextual information in a scene (Peterson & Gibson, 1993, 1994; Peterson et al., 1991; Vickery & Jiang, 2009). One such process is associated with a phenomenon known as figure-ground organization, in which the visual system delineates sets of features to either a foreground figure or a background (E. Rubin, 1921). This perceptual process has been experimentally probed by asking observers to report which of two flat 2-D shapes (black and white respectively) they perceived as an figure/background. This type of judgement is sensitive to prior exposure to known features. It has been demonstrated that pre-task priming could influence and enhance the judgements on which features constitute the figure and background (e.g., the participant more rapidly identifies a profile of a familiar shape, such as a lamp, as being the figure). Specifically, observers primed with randomly configured parts from a familiar figure discerned the familiar set of features as belonging to a figure more quickly than when primed with irrelevant sets of features (Cacciamani, Ayars, & Peterson, 2014).

This general advantage, in which higher level cognitive factors effect perceptual organisation, has been shown to provide fine-tuned benefits to the local grouping of Gabor patches. Familiarity, the predictability of the presented objects, and how easily an observer can identify a target object have all been shown to facilitate the grouping of Gabor patches into detectable closed contours (Sassi et al., 2014; Nygard et al., 2011; Sassi et al., 2012). These findings were, for the most part, similar to those benefits observed for the presence of bilateral symmetry. However, an important difference that has been uncovered by their program of study is that, unlike symmetry, whose benefits are limited to central vision, Sassi et al (2014) showed that the benefits of familiarity extend to the peripheral region of vision.

The perceptual organisation of local Gabor patches into a closed contour is therefore sensitive to not only systematic shape level regularities such as symmetry, but also unique sets of features that lend themselves to recognition. However, special configurations of features are not simply tied to a single object but can reoccur across the visual field. The contextual presence of these important features has been shown to effect the detection of objects.

4.2.3 The contextual and lateral enhancement of detection due to the simultaneous presentation of features and objects.

A large number of studies have demonstrated that the reoccurrence of features across the visual field can modulate the detectability of a target. These studies have frequently used Gabor patches to determine the contextual factors that influence the detection of localised features (e.g., contrast, orientation) and have been used to investigate complex patterns of both enhancement and suppression of detection. Using simple localised targets and flankers, the presence of discrete Gabor patches surrounding a target Gabor patches has been shown to facilitate the detectability of the low contrast targets. (Polat & Sagi, 1993; Adini et al., 1997; Bonneh & Sagi, 1999; Churan et al., 2009; Cass & Spehar, 2005; Chen & Tyler, 2001; Freeman et al., 2001; Huang & Hess, 2007; Mizobe et al., 2001; Katkov & Sagi, 2010; Polat & Tyler, 1999; Sterkin et al., 2008; Woods et al., 2002; Zenger & Sagi, 1996). Other complex effects have been shown to occur in which differences in the features of the Gabor patches (I.e. if the flanker Gabor patch orientation differs from that of a target patch that it is close to) can cause the suppression of detection processes (Tadin et al., 2003; Born, 2000; Pack et al., 2005; Churan et al., 2009; Spillmann, 1994; Troncoso et al., 2007; Petrov et al., 2007).

In turn, the ability to identity the features associated with the target (I.e., the observer is required to determine what the target Gabor patches orientation is) is similarly disrupted when presented with groups of surrounding flankers whose orientations are different from that of the target (known as crowding)(Bouma, 1970; Stuart & Burian, 1962; Pelli & Tillman, 2008; Toet & Levi, 1992; Levi, 2008; Levi et al., 2002; Parkes et al., 2001; Pelli et al., 2004). However, unlike simple Gabor patches that were directly adjacent to each other, Gaborized contours, as used in the previous experiment (see Chapter 3, p.51) occupy a region of the visual field. Hence, unlike the facilitory effects observed at a local level, these new findings indicate long range connections between different regions of the visual field that, in turn, influence a large number of local grouping processes across an entire contour.

For whole detectable objects, a number of other complex behaviours involving inhibition and enhancement of detection processes have been observed. For instance, the allocation of attention in a scene inhibits an otherwise prominent object moving across the visual field (Simons and Levin, 1997; Simons and Chabris, 1999). In turn, how rapidly a target is detected is facilitated by the presence of additional congruencies in the visual field (Todd, 1912; Miller, 1982; Toellner et al., 2011; Krummenacher et al., 2001, 2002a, 2002b; Ivanov & Werner, 2009; Grubert et al., 2011; Ben-David & Algom, 2009).

In the realm of contour integration, the presence of features in both an attended and unattended contour permits better detection of Gaborized contours in the peripheral, unattended regions of the visual field (Stojanoski & Niemeier, 2007). Unlike the methodology used in this experiment (that investigated how common features affect the detectability of unattended contours) the present experiments are focused on the role of unattended contours on the detectability of a central, attended target.

4.2.4 The effects of flanking contours, features and complexity on the detection of a target Gaborized contour.

In a previous study the effects of the presence of flanking contours on the detection of a central target contour was investigated (see Chapter 3, p.51). As with related experiments, in which perceptual organisation was enhanced by the presence of symmetry and familiarity features (Sassi et al., 2014; Nygard et al., 2011; Sassi et al., 2012), the detectability of the target contour was facilitated by the presence of flanking contours of the same shape. However, the pattern of the data, as well as a number of confounds identified in the methodology, could not rule out a role of the presence of specific features shared by both the target and the flankers. In other words, the presence of features in both a central, attended and peripheral unattended contour may have interacted in the contour integration process.

The facilitory effect of the presence of flankers could therefore be interpreted in two ways: (A) it is the result of a number of complementary perceptual processes that function together or (B) it is the result of a single lateral feedback mechanism that associates the shape of the flankers with the target contour and is more efficient when specific features (e.g., symmetry) increase the visibility of the flanking contours.

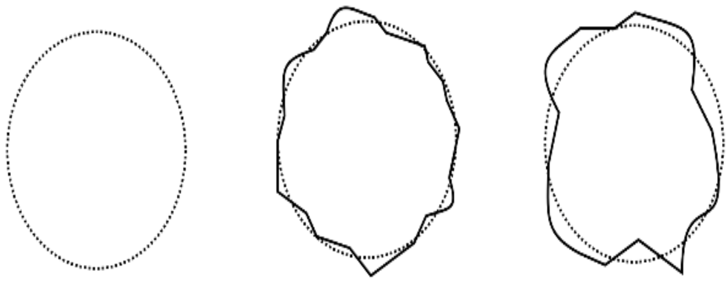

Figure 4.1: **Change in complexity due to local changes in orientation in a circle.**

The target contours presented were generated from a pre-existing shape, and, as orientation jitter was added to the contour the orientations result in lower visibility. Intuitively, if this is considered in terms of a target (Circle being detected at higher levels of orientation jitter the increasing changes to the boundary (from left to right) become more irregular, and as a consequence, more complex. If each point of jitter corresponds to both an inwards and outwards change then the overall area can be considered fixed and a change in the complexity of a Gaborized contour can be characterised as a general increase in perimeter length (Length of the dark black line). The compactness differential is the resultant difference in complexity between the contour at detection threshold and that of the initial complexity. For the purposes of this study, the compactness differential was estimated based on deriving a value for change in complexity per degree increase of orientation noise by using a manual procedure which used a selected range of stimuli generated for the experiment, for more details see appendix 3 (p.206).

The previous experiment attempted to normalise the influence of flanker visibility by surrounding the flanking contours with a set of Gabor patches with a single orientation (isolinear vertically aligned Gabors). However, by itself, the method could not be used to conclusively rule out the possible contribution of the Gabor field itself. In other words, the effects of the visibility of the flanking contours were confounded with the possibility of the noise field contributing to the target detectability in the control condition.

The present experiment combines the isolinear field with a metric that is sensitive to the complexity of the contours being presented. In other words, by combining an experimental method that increases the visibility of the flankers, and one that encodes the general difficulty of processing the shapes of both the target and flankers, it is possible to distinguish between the two explanations above.

The standard detection threshold/detectability of a target contour is based on the simple increase of 1-D orientation noise across the set of Gabor patches. However, this measurement does not take into account contextual distribution of Gabor patches such as the area over which the Gabor patches are organised and the relative locations of adjacent Gabor patches. Hence, it does not capture the fine-tuned difficulty of perceptual grouping.

One strategy is to formulate these results in terms of the whole shape. A measurement of the compactness of a shape (Zusne & Michels, 1962a, 1962b) for instance, combines the area and overall perimeter length of a contour to provide a unique measurement of the complexity of a shape (see equation 4.1). Changes in length, such as those that would occur if the noise Gabors were incorporated into the integrated contour, would therefore impact on the overall compactness of the detectable contour shape.

A measurement of compactness could therefore be plausibly used to capture the complexity of target detection, assuming the visual system was attempting to extract a smooth 'virtual contour' from the noise field (for a general theoretical overview of the variety of compactness measurements across, say pixelised or smooth shapes, see Montero & Bribiesca, 2009). Compactness in its traditional form has one particularly important mathematical property that makes it useful for psychophysical interpretation: Compactness is optimal when the shape being measured is a circle (i.e., when it has a value of 1) and, therefore, can be interpreted as the circularity of a contour. Circularity has been shown to be important to the v4 region of the visual cortex (Zusne & Michels, 1962a, 1962b; Gallant et al., 1993, 1996; Wilkinson et al., 2000; Wilson & Wilkinson, 1998; Dumoulin & Hess, 2007). Hence, the measurement provides further neurophysiological context to the findings of the experiment.

As it has been stated, the important point to note in the use of orientation jitter is that it presents a potential target contour with differing complexity from its original underlying shape. It is plausible that since the visual system does not ′know′ the shape of the to-be-detected target, it is simply trying to extract the simplest closed shape from the noise field.

The orientation jitter applied to the target contour Gabors combined with nearby background noise Gabors present a multitude of potentially integrable shapes, which have an average complexity that is a combined effect of the underlying complexity (compactness) of the generating shape and the complexity introduced into potential solutions by the orientation jitter. If the visual system is trying to integrate the simplest possible closed shape (highest compactness, smoothest perimeter) the task should become more difficult as the noise increases, but not necessarily in a simple linear relationship with increase in orientation noise.

The same level of orientation noise may represent a much larger change in compactness for one shape compared to another depending on what the original compactness of the generating shapes was. In other words, the actual value of orientation noise is not necessarily a good direct measure of the difficulty in contour integrability. To accommodate for this, one solution is to treat the effect of orientation jitter on the complexity of the target as an alternative measurement of the increase of difficulty of detection (see Figure 4.1). The motivation for doing so is that underlying complexity of the target is contextual dependent on the distribution of the Gabor patches. Once these contextual differences in shape are taken into account, the addition noise should theoretical have a linear increase in overall complexity for each additional degree of orientation jitter added.

Complexity, here defined as the reciprocal compactness value, consists of the ratio of the squared perimeter length of a smooth contour, divided by the enclosed area (see Equation 4.1 for details). Hence, the addition of orientation jitter at fixed points in a closed smooth contour corresponds to an increase in the perimeter length, and hence, the complexity of the target in-trial. To relate orientation jitter (the original dependent variable) to a measure of contour complexity change, a compactness differential is calculated. This involves (A) estimating the change in the compactness of a smooth contour caused per degree of orientation noise (B) using this value to calculate the compactness of the target contour at the detection thresholds and (C) subtracting the compactness at threshold from the initial compactness of the generating contour. The resultant value corresponds to the independent change in complexity that occurs before the visual system is incapable of grouping the Gabor patches into a smooth contour. Due to differences in extrema between complex and simple shapes, the perimeter length increase per 1 degree of orientation jitter is expected to be greater for more complex shapes. Hence, this difference would result in larger initial compactness differentials and higher detection thresholds for more complex target contours. Correspondingly, a facilitation effect can be interpreted as an increase in the complexity differential for any given shape at threshold.

The usefulness of this approach is that it permits further analysis of the dataset in terms of whole contours (i.e., not simply the alignment of the Gabor patches, but the contour suggested by the local orientations). The primary assumptions of the compactness differential are that the visual system is using localised orientation information to determine a smooth coherent contour. This therefore differs from a perceptual mechanism that 'knows' the shape of the object it is searching for and compensates for the noise across the contour, which would be captured fully by the magnitude of the orientation jitter added to the contour. Thus, in this study, the effect of the presence of flankers on target contour detection will be examined both from the standpoint of the original dependent variable (degree of orientation noise jitter) as well as the alternative measure of the compactness differential.

4.2.5 Experimental summary

The purpose of the experiment was to determine the role of the presence of high level features and shape complexity (compactness) in the flanker facilitation effect. Specifically, the detectability of a Gaborized contour (a contour consisting of spatially separate Gabor patches arranged to form a shape) was examined in the presence of two horizontally flanking contours of similar or dissimilar shapes. Two shape factors (familiarity and bilateral symmetry) were used to create four groups of target contours. The selected shapes were then measured for their shape compactness (circularity) (Zusne & Michels, 1962a; Montero & Bribiesca, 2009).

The detection threshold for all contour shapes was measured for three different conditions in which the target contour was presented alone: (control); with flanking contours of the same shape (same condition); with flanking contours of a different shape (different condition). As in previous studies, contour detection thresholds were defined as the maximum amount of orientation noise that could be added to the contour before it became undetectable, with higher levels of noise indicated more enhanced levels of detectability. However, in the present study, an alternative dependent measurement was also defined, referred to as the compactness differential. This is defined as the difference in complexity between the initial shape used to generate the target contour, and the estimated complexity of the contour at the point at which detection failed.

The presence of a flanker facilitation effect is defined as the outcome, where the detection threshold of a target in the presence of flankers is lower (higher noise tolerated) than in the control non-flanker condition. In terms of the alternative dependent measure, a flanker facilitation effect would be entailed by a larger compactness differential in the flanker condition compared to the control condition. Moreover, greater systematicity in the flanker facilitation effect when expressed in terms of a compactness differential would imply that compactness/complexity was a more effective measure of contour integrability than simply the level of orientation noise, and furthermore confirm that the flanker facilitation effect was occurring at the level of the probabilistic integration of available Gabor patches into the most plausible compact closed contour, rather than a process of applying a template match to noisy Gaborised contour extraction of the most likely closed contour.

4.2.6 Methodology

Participants

In total, 26 paid volunteers signed up for the experiment but 7 did not provide a full set of data suitable for analysis (2 could not perform the task and 5 did not turn up for a second session). Of the 19 participants who performed the full experiment: 14 were paid undergraduate volunteers (5 per hour); 5 were postgraduate students or members of university staff who performed the task without payment. 17 of the participants were female. The age range was 17 to 50 years. Each participant performed two sessions (1 hour per session). Two breaks were provided at approximately 1/3 and 2/3 of the way through the session for as long as the participant wished. All participants had normal or corrected-to-normal vision. Ethics was granted by the St Andrews University Teaching and Research Ethics Committee (UTREC - Ethics reference number: PS7638).

Apparatus

Experiments were presented on a Dell 2407WFP LCD display with a resolution of 1920x1200 with a refresh rate of 60 Hz. The viewing distance was 57 cm. Participants viewed the screen from a chin/head rest. The experiment was implemented using Matlab (Mathworks, Inc.) using the psychophysics toolbox utilities (Brainard, 1997). Statistics were performed in R (R Development Core Team, 2008) and presented using Gnuplot (Williams & Kelley, 2011).

Stimuli

The stimuli were created using the Grouping Elements Rendering Toolbox (Demeyer & Machilsen, 2012) based on Matlab programming language. The staircase procedure used to present the stimuli for each trial was run using the Palamedes Toolbox

(Prins & Kingdom, 2001).

The stimuli consisted of two components: A set of sine waves windowed by a Gaussian envelope, known as a Gabor patch, and a generating shape combined with a set of Gabor patches to generate the stimuli presented to the observers. The Gabor patches consisted of a sine wave luminance profile of frequency 2 cycles/deg and the 2-dimensional Gaussian envelope with a Gaussian standard deviation (sigma value) of 3 pixels. The phase of each Gabor patch was randomised by 90 degrees.

The panel was primarily populated with a field of randomly positioned, non-overlapping, randomly oriented Gabor patches (referred to as the noise field). The average initial minimum spacing between Gabor patches in the noise field was around 16.5px.

To create the target contours, a set of generating shapes was combined with a number of Gabor patches. The generating shapes are presented in Figure 4.2. The shapes were chosen to encode two factors: The presence of bilateral symmetry, and observer familiarity. Four groups were generated consisting of: familiar and bilaterally symmetric, unfamiliar and bilaterally symmetric, familiar and asymmetric; and unfamiliar and asymmetric contours.

To take into account differences in the complexity of the shapes used, the reciprocal compactness values (here defined as complexity) for each shape were recorded (see Figure 4.3). The equation for complexity divides the squared value of the absolute length of the perimeter of the shape by the area it encloses (Equation 4.1).

$$C = \frac{(P^2)}{(4 * \Pi * A)} \tag{4.1}$$

Where C is the complexity value of the shape, P is the length of the perimeter of the generating shape, and A is the enclosed area for the generating shape. The resulting number is a dimensionless ratio. The optimal value, 1, corresponds to the compactness of a circle in which the minimum length of contour is distributed along

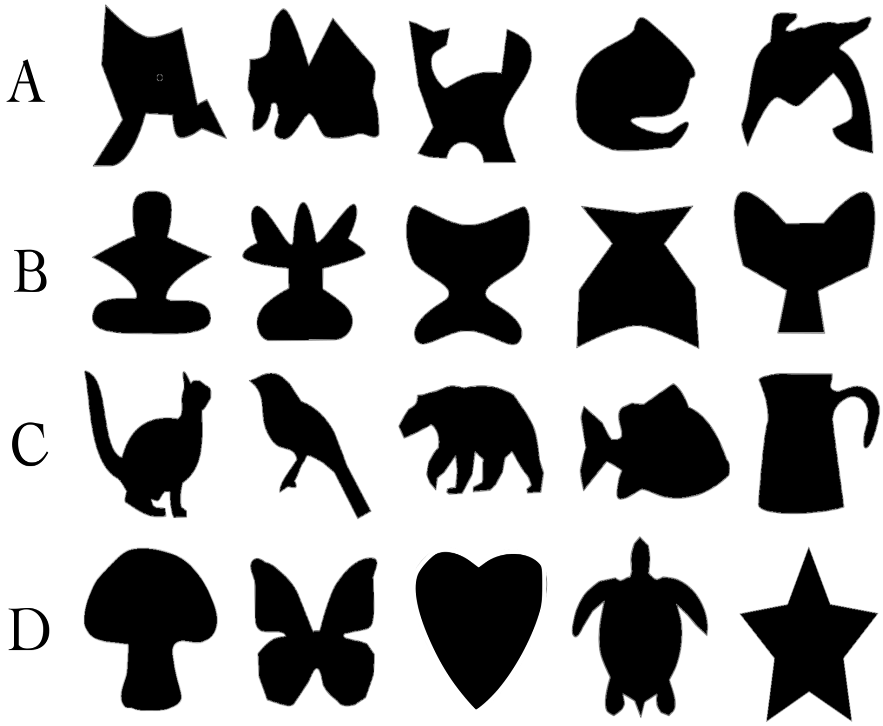

Figure 4.2: **Shapes used to generate target and flanker Gaborized contours.** Four groups of generating shapes were created using outlines of everyday objects (e.g., Cat, Jug, Trousers) and a set of geometric forms of varying regularity (e.g., Hexagon, non-regular curvilinear shapes). Group A (Row 1) consisted of asymmetric unfamiliar shapes. Group B (Row 2) consisted of bilaterally symmetric unfamiliar shapes. Group C (Row 3) consisted of asymmetric familiar shapes. Group D (Row 4) consisted of bilaterally symmetric familiar shapes.

the maximum enclosed area.

A set of approximately 21 Gabor patches were placed at intervals along the perimeter of the generating shape (Figure 3.2). The width of these intervals was randomised. The maximum width to which subsequent Gabor patches could be positioned was a single wavelength. Inspections were made of the subsequent Gaborized contours and minor adjustments (+/- 2 Gabor patches) were made if the resultant contour lacked corners or extrema. The orientation of these individual Gabor patches corresponded with the local orientation of the underlying generating shape.

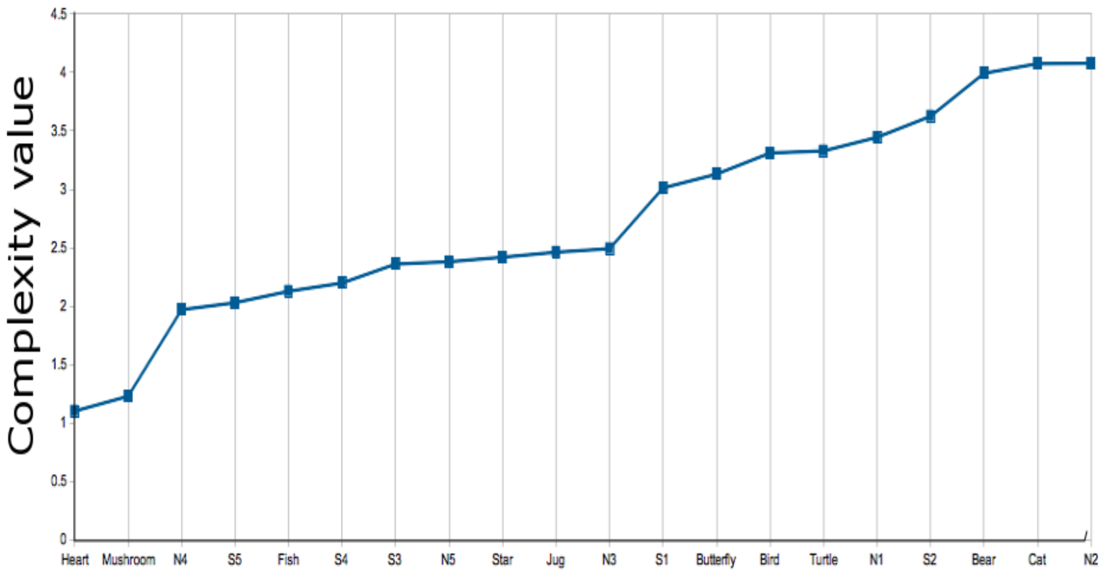

Figure 4.3: **The individual complexity values for the generating shapes** The complexity (the reciprocal value of compactness, which is the square of the length of a contour divided by the area it encloses) for each shape (y-axis)used as a target contour was measured (x-axis). This range was approximately linearly and monotonic. The groups of shapes presented in Figure 4.2 contained a range of complexity values between the values of 1 to 4.5.

The stimuli presented in a trial were presented on a grey rectangular panel (14x8 degree) which was placed on an otherwise black screen. The panel was populated with a field of randomly positioned, non-overlapping, randomly oriented Gabor patches (referred to as the noise field). The Gaborized contours were then embedded in the noise field so that there was no overlap with the randomly orientated noise Gabor patches. The Gaborized flanker contours were embedded in a Gabor field whose Gabor patches were aligned vertically. This was done based on the previous study in order to maintain visibility for more complex flanker shapes (see Chapter 3, p.51).

The combination of Gaborized contour and the noise field introduced possible variations in the density of the overall panel of Gabor gratings. To assess the presence of probabilistically significant density differences, and to subsequently adjust the relative locations of the set of Gabor patches, a method native to the stimuli generating program, G.E.R.T, was used. This employed a Voroni tessellation to isolate the immediate area surrounding each Gabor patch and trace it as a polygon. The surface areas for the polygons were computed and compared across both the noise field and the embedded contours to determine that the surface areas were reasonably uniform across the whole stimuli.

The Detectability of the target contour was varied by adding orientation noise jitter to the individual Gabors making up the contour . The amount of orientation noise jitter added across the set of Gabor patches was sampled from a normal distribution. The maximum value such orientation jitter could take was the range of 90 to -90 degrees adjustment from alignment.

In these experiments the results are reported as the magnitude values (e.g., a range of 90 to -90 degree difference corresponds to a maximum magnitude of 180 degrees). For example, in these experiments 40 degrees of noise jitter (-20 to 20) represented a highly visible contour with a low level of orientational noise jitter, while 120 degrees of noise jitter (-60 to 60) represented a contour with low visibility with a high level of orientational noise jitter. The effects of adding orientation noise to a smooth contour are presented in Figure 3.5.

The central Gaborized target contour was presented with and without additional flanking contours in one of the following configurations: (1) the control condition in which the target was presented alone (2) the same condition in which the shape of a target was paired with the shapes of the two Flanking contours (3) the different condition presented the target flanked by two contours of a different shape than the target, but matching each other. The flankers (when present) were displayed to the left and right of the target so their centroid aligned with the target centroid, and the horizontal distance between centroids was approximately 4.7 arc degrees. Examples of these conditions are presented in Figure 4.4.

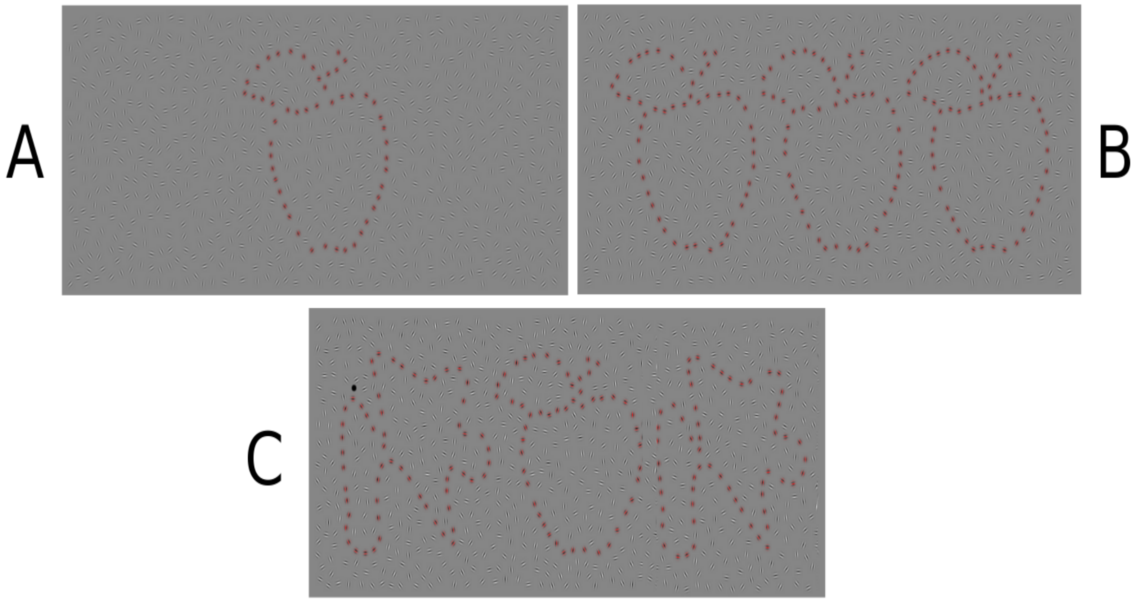

Figure 4.4: **Conditions presented to participant in the experiment**
In these examples the contours are defined by a set of collinear Gabor patches aligned to a generating shape with a set of randomised Gabor patches both in and without the contour perimeter (shown in red for demonstrative purposes only. Three conditions were presented in which the target was paired with either no or two adjacent flankers. These were (A) the control condition in which the target contour was presented alone (B) the same condition in which the target contour was simultaneously presented with two flanking contours with the same shape, and, (C) the different matching condition in which the target contour was simultaneously presented with two different flanking contours.

4.2.7 Procedure

Each trial consisted of two stimulus presentation, a target-present panel and a target-absent panel. In the target-present panel the target was displayed centred horizontally. The target absent panel was identical to the target present panel except that there was no target contour present.

In order to prevent any gross differences in perceived density of the two types of panels the average density of the target absent panels was generated by matching it to the value of the target present condition. The number of Gabor patches in the target-present and target-absent panels was therefore the same. The density value was further used to create a set of 5 inter-trial display panels for each set of presentation panels. These inter-trial display panels contained no contour information as they contained randomly positioned and orientated Gabor patches only.

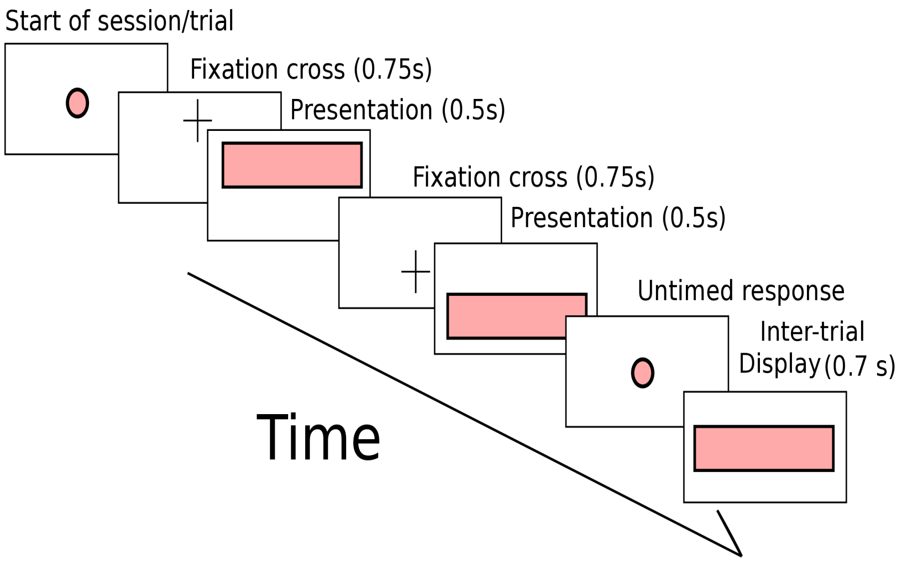

Figure 4.5: **The time course of a single trial**
Each trial consisted of two sequentially arranged stimuli with a common set of flankers and randomised noise background with a presentation of target-absent or target-present randomly in the Left or right position on the monitor. Prior to the presentation of the stimuli a fixation cross was placed onscreen to direct the attention of the participant to the correct location.

The sequence of stimulus presentation (Figure 4.5) involved an initial fixation cross at the center of the main display panel (750 ms), followed by a fixation cross appearing at the upper or lower half of the overall panel. This was followed by the presentation of either a target-present or target absent stimulus panel for 500 ms. After this time, a fixation cross appeared at the opposite location (lower or upper panel) and was followed by either the target-absent or target-present panel (depending on what was previously shown. A circle was presented with no fixed duration in which the participant was asked to respond if a contour was present in either the upper or lower panel. Once a response was recorded a inter-trial display was presented for 700ms and a central red circle was flashed up (200ms) to indicate the beginning of a new trial.

The first presentation panel for any given staircase for each contour consisted of Gabor gratings aligned to the underlying generating shape. The degree of orientation noise was varied according to participant responses using a weighted 1-up 1-down staircase procedure targeting approximately a detection threshold of 67 percent (Kaernbach, 1991). This rule was adopted after an initial 3 trials. The step size in the initial 3 trials was 16 degrees of noise. This large step size was intended to reduce the number of steps required to approach the detection threshold level. After the first 3 trials, step size was reduced to 4 degrees. If the participant was incorrect at the lowest level of noise the level of noise remained the same during the first three trials.

To extract the detection threshold, the staircase procedure varied the magnitude of the added orientational noise jitter until the participant was no longer able to detect the shape (Figure 1.9). The initial level of noise jitter for each staircase was at 12 degrees of noise. That is, the contour was extremely visible and detectable to all participants.

Each staircase was terminated after 15 reversals occurred for the individual contour and the threshold was calculated by taking the mean value over which the last 10 reversals took place. In circumstances where less than 15 reversals occurred by the end of 50 trials the individual staircase was terminated, if less than 8 reversals took place the staircase was removed from the dataset. Here, the detection thresholds are presented in the reciprocal detectability values corresponding to the absolute magnitude of orientation noise jitter added per trial. Therefore a decrease in the detection threshold corresponds to an increase in the detectability of the shape under greater degrees of orientation noise jitter.

A number of participants could not perform the task for all contour types (that is, for complex contours such as the cat their performance was around the lowest level of additional noise). Additionally, a number of contours staircases over-shot the detection threshold and did not return in the allocated number of trials. Two limits corresponding to detectability values of 30 and 160 were chosen and data that was above or below these values were discarded.

Finally, the compactness differential measure was calculated based on the specific level of orientation noise at threshold for each stimulus condition and the compactness of the generating shape. This was a three step process that involved: (A) determining the change in contour length caused by one degree of orientation noise; (B) using this value to calculate the compactness of the target contour at the detection threshold; (C) taking the difference between the value in B and the compactness of the generating contour. The equations are presented in equation 4.2 below.

$$\Delta = C_T - C_C \tag{4.2}$$

Where delta is the compactness differential where the subscripts are: T, the complexity of target contour under the target-flanker conditions, C, the complexity of the target contour in the control condition.

Data analysis

The detectability of the target-contour was analysed by taking the mean of detection thresholds and computing a factorial 3x2x2 ANOVA with the presence of additional flankers, presence of bilateral symmetry in the target contour, and the recognisability of the target contours as factors. Additionally, he compactness differential was computed for each target shape and plotted as a function of the underlying compactness of the generating contour. A method of least-squares was used to compute two fits to the resultant data. One fit corresponding to the dataset of the control condition, and the second fit corresponding to the dataset of the same condition. These fits relate the mean observer performance (in terms of complexity) across all individual contours with each other.

4.3 Results

The mean thresholds averaged across all contour groups and participants are presented in the bar plot in Figures 4.6 (p.118) and 4.7 (p.119). The results (in terms of the specific factors, bilateral symmetry and shape familiarity) are presented in the bar plots in Figure 4.6a (bilateral symmetry), and Figure 4.7b (familiarity). Figure 4.7 also plots the detection thresholds of bilateral symmetry/asymmetric contours in terms of the flanker condition. As described in the data analysis section, a factorial 3x2x2 ANOVA was performed with the three factors of: presence of additional flankers, presence of bilateral symmetry in the target contour, and the recognisability of the target contours. Additionally, the two way and three way interactions between the factors were considered.

There was a main effect of the condition of flanker contour shape relative to the target contour shape ($F(2,36)=8.215$, $p<0.01$), where the overall mean threshold for a target contour was lower (higher detectability) for the target contours in the same condition in comparison with the control and different condition; Figure 1.12). The mean detection thresholds were calculated on the basis of the symmetry/asymmetry factor is presented in Figure 1.13a. The combined data for all target contours with and without symmetry showed that there was an increase in the detectability associated with the presence of bilateral symmetry ($F(1, 18) = 4.72$, $p < 0.001$). This was an expected finding based on previous studies (described in section 4.2, p.96).

There was, however, a significant interaction between the symmetry and familiarity conditions ($F(2, 36) = 32.39$, $p<0.001$). The interaction was expected, as certain features (bilateral symmetry) are prominently associated with familiar shapes. However, there was no main effect of familiarity ($F(1, 18) = 5.513$, $p= 0.231$). This was unexpected as previous studies had indicated that familiarity was a factor in contour integration tasks of this kind. There were also significant interactions between familiarity and condition ($F(2, 36) = 21.72$, $p<0.001$) and a three way interaction between symmetry, condition and familiarity ($F(2, 36) = 3.838$, $p<0.05$).

To confirm that the data was not biased due to non-normal distributions or non-homogeneous variation both a Levene′s test (Test statistic = 2.1289, $p = 0.322$) and Shapiro-Wilks tests were conducted (condition ($W=0.8$, $p = 0.46$); familiarity ($W=1.63$, $p = 0.2$); and bilateral symmetry ($W=1.19$, $p = 0.2761$). The tests confirmed that the data was normally distributed and that the variance was homogenous across the factors in the experiment. While there is a clear indication that the results are consistent with a general flanker facilitation effect and an enhancement due to the presence of bilateral symmetry, the interaction between familiarity and symmetry together may be due to an unavoidable confound introduced by the possibility that (a) symmetry itself was being used as a form of familiarity, and, (b) that symmetric shapes are generally familiar. Due to the complexity of this issue and its implications it is outside the scope of this thesis.

The present results are consistent with the previous findings (see Chapter 2, p.30) showing increased detectability when a target contour was paired with flankers of the same generating shape. The trend of the data showed an expected increase in the detectability of a target contour due to the presence of bilateral symmetry. A further enhancement of the flanker facilitation was observed when the target and flanker had both the same bilaterally symmetric shape.

4.3.1 A fit of the increase in complexity due to the addition of orientation noise with respect to the initial compactness of the target contour.

A least-squares quadratic polynomial fit was performed on the compactness differential as a function of the complexity of the shape used as the target contour (Using the Curve Fitting Toolbox in Matlab). These were produced for both the control and same condition.

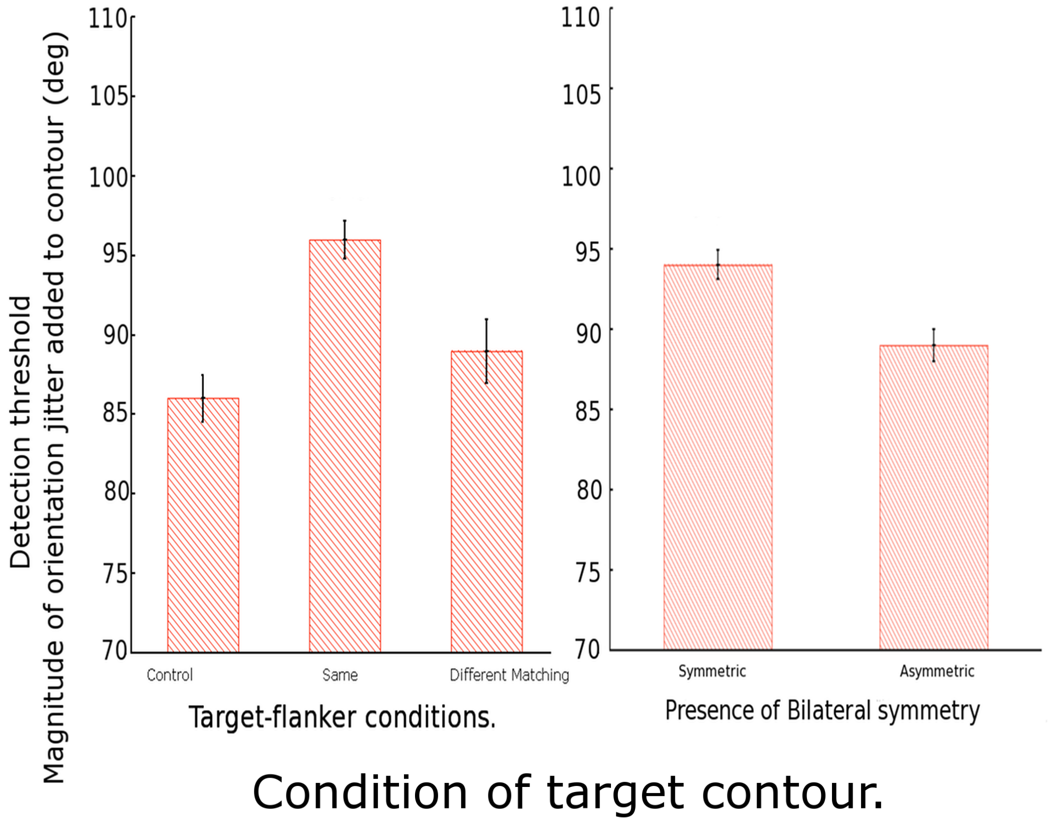

Figure 4.6: **The mean detection thresholds of the target contour as a function of the target-flanker and symmetry conditions.**
The detection thresholds (y-axis) are presented against each of main conditions run during the experiment(x-axis). The plotted conditions are: (Left) the target-flanker conditions, which contained three conditions (e.g., control, same and different matching and (Right) the presence or absence of bilateral symmetry. The plotted data are the magnitude of orientation jitter added to a central target contour at a detection threshold of approximately 70 percent proportion correct averaged over all participants (n=30). Error bars represent the standard error of the mean.

These fits were made to the whole dataset in terms of individual contour shapes. Therefore, it is possible that the error for the range of points corresponding to a single contour varies across the whole dataset for contours due to varying shape complexity. In this case it would be expected that for more difficult trials (those with highly complex shapes) the variance would be greater than for those trials

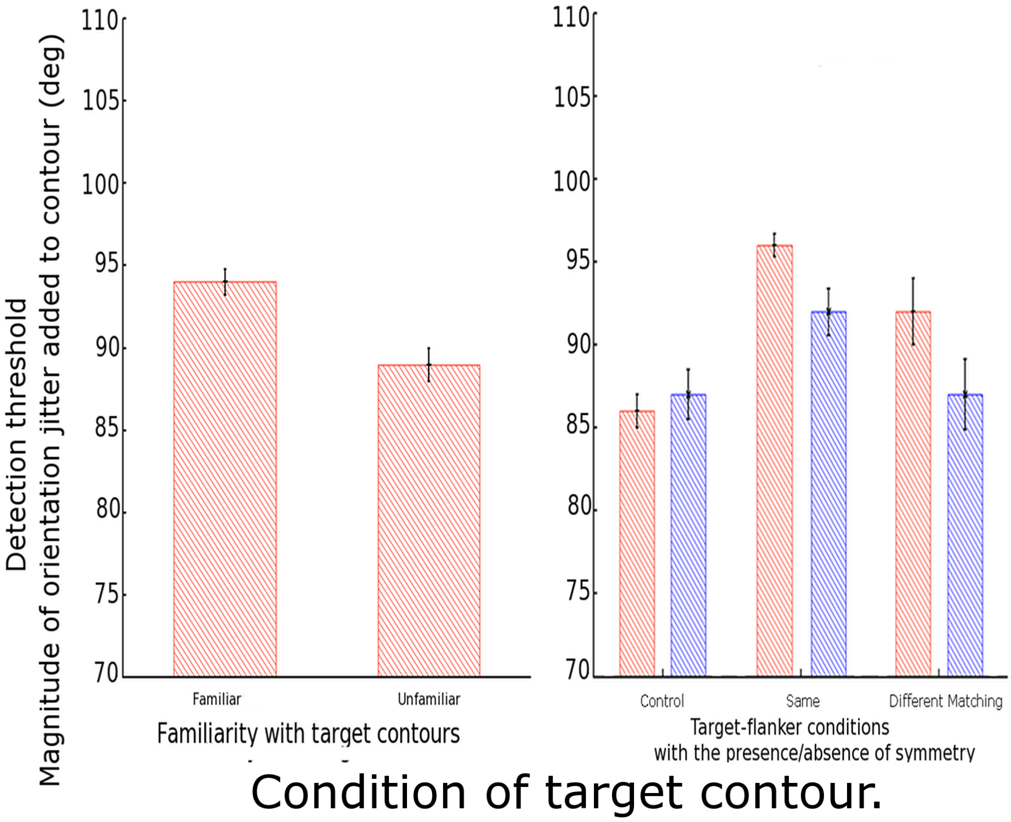

Figure 4.7: **The mean detection thresholds of the target contour as a function of target familiarity and both the target-flanker and symmetry conditions.**

The detection thresholds (y-axis) are presented against each of main conditions run during the experiment (x-axis). The plotted conditions are: (Left) the presence/absence of a familiar contour shape and (Right) the presence or absence of both condition and bilateral symmetry. In this plot the blue bars are the asymmetric contours and the red are the symmetry contours. The plotted data are the magnitude of orientation jitter added to a central target contour at a detection threshold of approximately 70 percent proportion correct averaged over all participants (n=30). Error bars represent the standard error of the mean.

whose contours represented simpler shapes, and that this would result in greater number of outliers at one end of the fit. To reduce the effect of outliers a weighted least-squares regression was used.

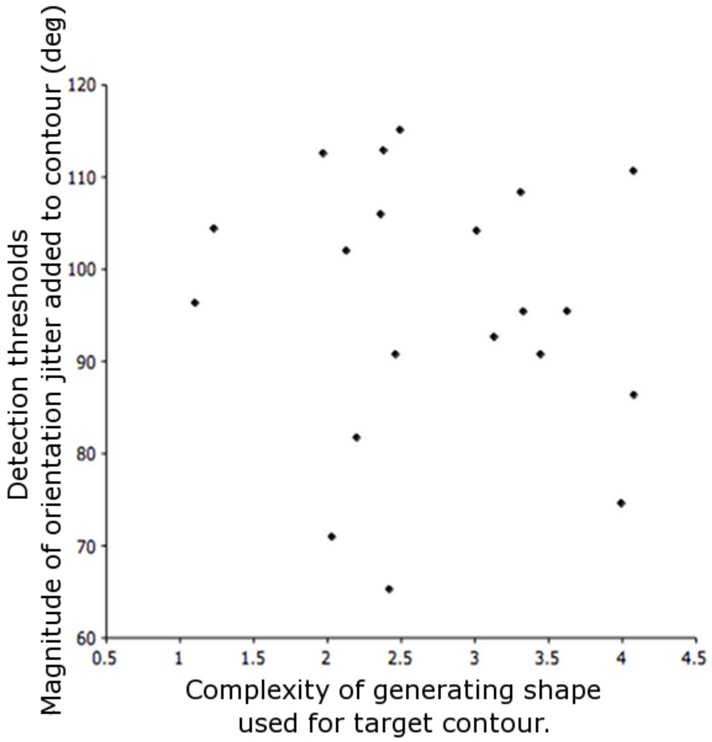

Figure 4.8: **The mean detection threshold as a function of the complexity of the shape of the target contour in the control condition.**
The plotted data is the detection thresholds (y-axis) from the control condition versus the complexity of the shape of the contour (x-axis). There is no systematic relationship that is discernible between how complex the target is, and the amount of orientation jitter than can be tolerated before detection fails.

Specifically, a bisquare weight (Heiberger & Becker, 1992) was used to minimise the effects of outliers. This method simultaneously performs a standard least-squares fit while minimizing the effects of outliers. It does so by weighting points near the centre line fit to the majority of the dataset and reducing the weight for each data point the further the each data point is from the line.

First, the values of the detection threshold in terms of the original dependent variable (noise magnitude) are plotted for each contour shape as a function of the shapes complexity (1/compactness), where the shapes are ordered along the x-axis as increasing values of complexity. These mean threshold values for the control and same

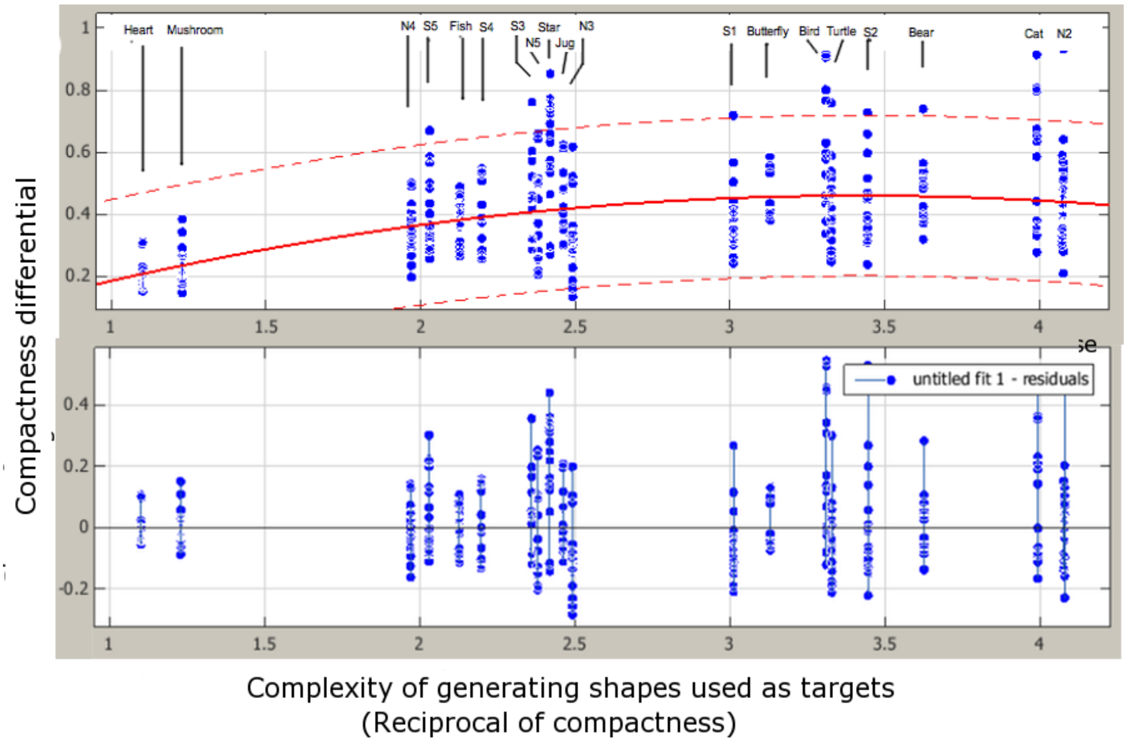

Figure 4.9: **The compactness differential for individual contours as a function of the complexity of the initial contour shape in the control condition.** The compactness differential results (y-axis) are presented against the initial complexity of the contour shape being detected (x-axis). The red line represents the method of least squares fit, while the broken red line represents the 95 percent prediction intervals. The lower graph presents the residual compactness differentials compared with the estimated fit.

conditions for all subjects are plotted in Figures 4.8 and 4.10 respectively.

From the graphs it is apparent that there is no obvious relationship between the mean detection thresholds and complexity of the shape. This suggests that if contour complexity is a critical factor in contour integration and flanker facilitation, then assessing detectability directly as a value of orientation noise level may not adequately capture the pattern of results. For this reason, as mentioned previously, a new measure called the compactness differential (the difference in compactness between the initial contour and the contour at detection threshold) was devised.

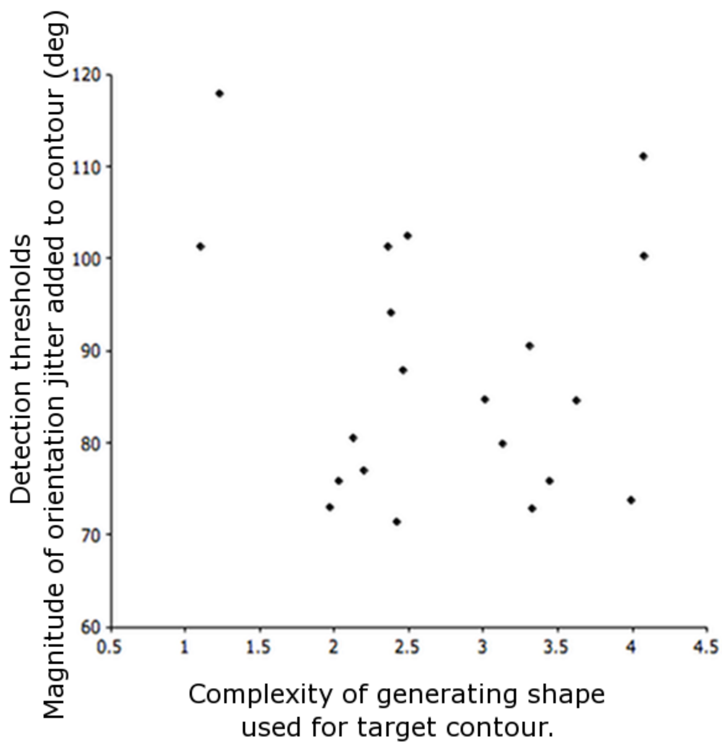

Figure 4.10: **The mean detection threshold as a function of the complexity of the shape of the target contour in the same condition.**
The plotted data is the detection thresholds (y-axis) from the control condition versus the complexity of the shape of the contour (x-axis). There is no systematic relationship that is discernible between how complex the target is, and the amount of orientation jitter than can be tolerated before detection fails.

The importance of this factor is that it recasts the original dependent measure (orientation jitter) as a change in compactness that accounts jointly for the both the underlying compactness of the generating shape and the effect on compactness for that specific shape due to the addition of noise. The compactness differential (at threshold detection) is plotted for all shapes as a function of the shapes compactness separately for the control and same conditions in Figures 1.17 and 1.18 respectively.

In comparison with the plots in terms of orientation jitter (see Figures of 4.8 and 4.10), there is a more systematic trend across the dataset when recast as compactness differentials (see Figures 4.9 and 4.11). This is true for both the control and

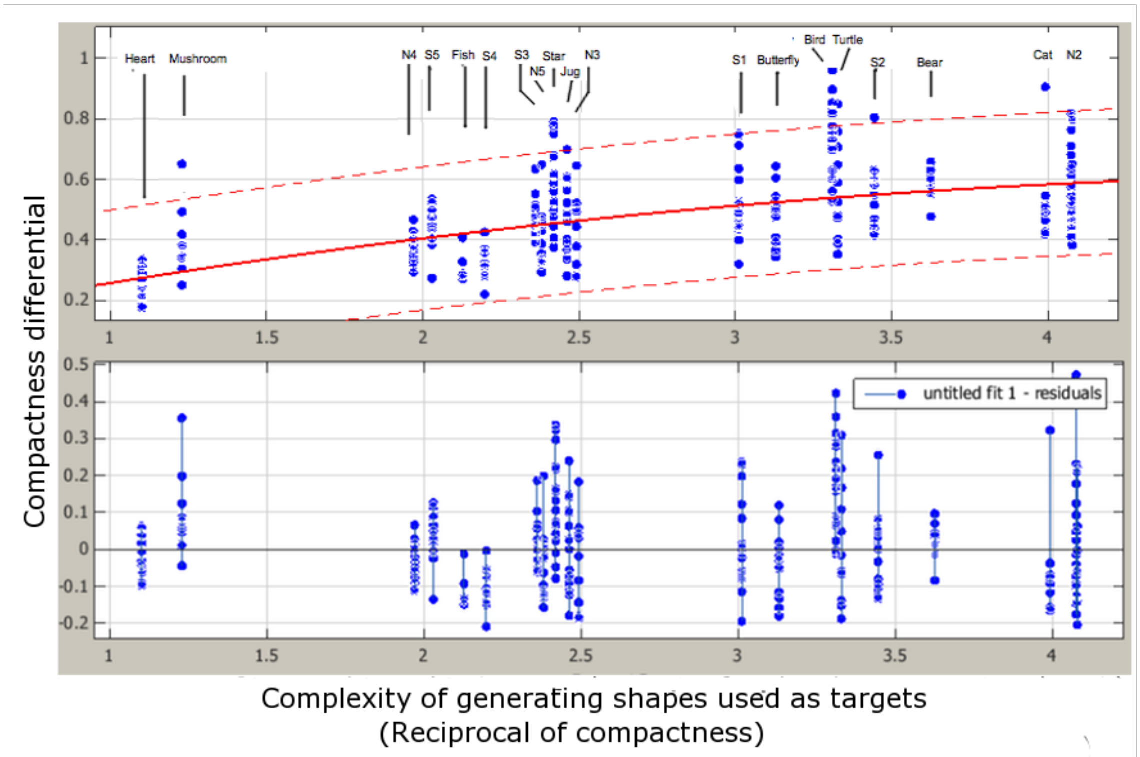

Figure 4.11: **The compactness differential for individual contours as a function of the complexity of the initial contour shape in the same condition.** The compactness differential results (y-axis) are presented against the initial complexity of the contour shape being detected (x-axis). The red line represents the method of least squares fit, while the broken red line represents the 95 percent prediction intervals. The lower graph presents the residual compactness differentials compared with the estimated fit.

same conditions. In both conditions there is a general monotonic increase in the compactness differentials as a function of the initial complexity of the target shape. However, in the control condition there is also a decrease at the highest values of the compactness differential. More specifically, for the control condition, the method of least-squares fit was a quadratic (Degree 2) polynomial fit had an R-squared value that accounted for 37.34 percent of the variation observed across the dataset. The data was normalized by a mean of 2.726 with a standard deviation of 0.87. The summed square of residuals, SSE, was 5.746. The root-mean-squared error was 0.1312. The compactness differentials for the majority of target contours increased with increasing complexity (in the range of C = 1 to 3). However, beyond this range the compactness differentials (for shapes with C $>$ 3) decreased in magnitude.

For the same condition, the fit was also a quadratic (degree 2) polynomial, and this fit had an R-squared value which accounted for 41.01 percent of the variation observed across the dataset. The Data was normalized by a mean of 2.71 with a standard deviation of 0.82. The summed square of residuals, SSE, was 4.115 . The root-mean-squared error was 0.12. Unlike the control condition, in this case, the compactness differentials showed a consistent monotonic increase even at the higher levels of shape complexity (C$>$3)

The general relationship between the compactness differentials and the complexity of the target contours was similar for both the control and same condition with increasing compactness differentials for increasingly complex contours. However, a clear and nearly constant increase in the compactness differentials in the same condition is evident, which shows that there was a consistent facilitory effect of the flanking contours, resulting in the detectability of contours at a higher level of complexity compared to the control condition.

Comparison of fits of the control and same conditions

The resultant fits were then compared to assess the flanker facilitation effect. The control condition was used as a baseline fit with the facilitation or suppression effects being the difference in the two fits. The comparison is presented in Figure 4.12.

There were three key criteria for assessing if the control and same conditions demonstrated that the flanker facilitation effect is performed using the extraction of a smooth contour (a feedback contour integration process) or a noise minimisiation process (a template is matched to the target region).

Firstly, the overall shape of the two fits should be the same. That is, as the same condition includes the performance for the detection of the target contour alone

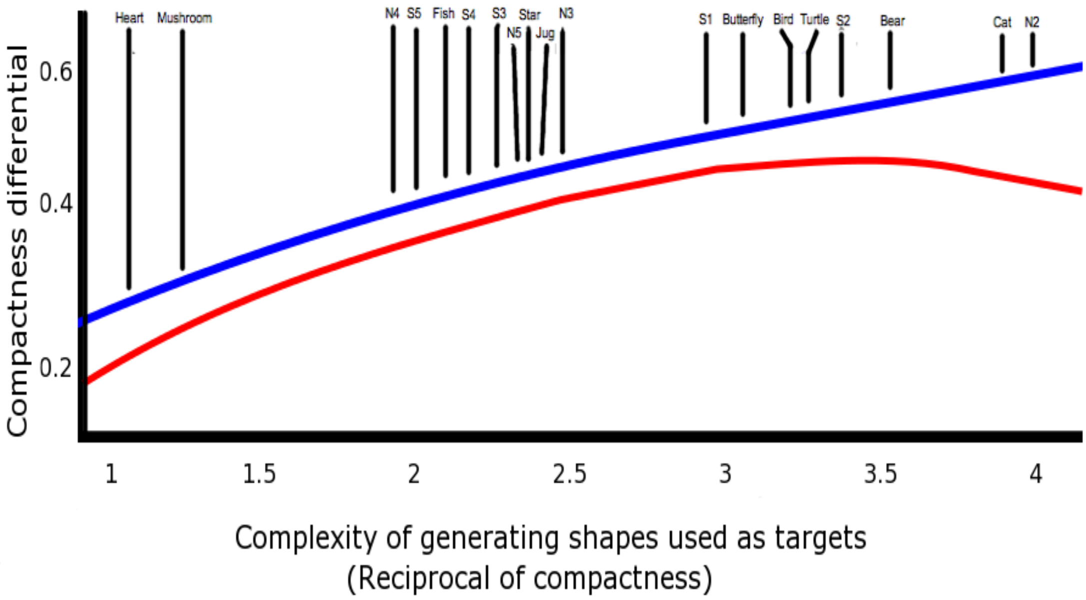

Figure 4.12: **Comparison of the quadratic fits of the compactness differential as a function of the complexity of the target contour in the control and same conditions.**

The compactness differentials (y-axis) for the complexity of the target contour (x-axis) for the control (blue) and same (red) condition are presented against each other.

it should reflect the relative complexities of all the contours used. Secondly, the in-condition results should be monotonic as this reflects the participant detecting the whole central contour presented. Thirdly, that the increase of differential effect should be relatively uniform corresponding to the same degree of facilitation for all target contours paired with flanking contours of the same shape.

Generally, the shape of the overall fit (Figure 4.12), the relative detection performance of the in-condition datasets was similar. One substantive difference concerned the non-monotonic behaviour of the control condition. This contrasted with the same condition fit that was indeed a monotonic behaviour. In addition, the overall monotonic behaviour in the same condition suggests that in the regions where the control dataset did behave monotonically, the facilitation was similar for these conditions. However, in the region of non-monotonic behaviour in the control condition it deviated from this pattern.

While this non-monotonic behaviour was unexpected it is, interestingly, more consistent with a flanker facilitation effect that is permitting a more accurate extraction of a smooth contour. More simply: In the control condition the noise field and the target contour are interacting, potentially removing subregions of the target contour, hence the observer is detecting shapes that are more compact than they are expected to be. When flanking contours were present the pattern of results became more consistent with the detection of the whole target contour. Hence, the added information that the flanker facilitation effect is providing for the target detection process appears to be making the whole process less subject to interactions from the noise field.

4.4 Discussion

The over-arching purpose of the present experiment was to more closely examine the factors the underlying facilitatory effects of flanking contours surrounding a target contour (see Chapter 3, p.51). These findings contained a possible confound, involving bilateral symmetry, triggering perceptual processes connected with feature-based attention. This experiment demonstrated that the flanker facilitation effect was tied to the shape of both the target and flanker contours, and also, that bilateral symmetry did indeed appear to increase the magnitude of this enhancement.

It is possible that this secondary finding represents a complementary detection process. With an observer detecting a bilateral symmetry in the target region, and that it was this detection process that was facilitated by the presence of other symmetries. In other words, it suggests that there is a second long range perceptual mechanism in which there are interactions between symmetries in the visual field. However, these results could also be explained by the possibility that bilateral symmetry was making the flanking contours more visible and therefore enhancing access to the relevant visual information. That is, the flanker facilitation effect is enhanced due to visual system having greater access to the relevant psychophysical features that it uses to perform contour integration due to the processing advantage of symmetric contours.

This would be consistent with work by Stojanoski and Niemeier (2011). In their study it was demonstrated that having a common feature (either shape or motion cue) between attended and unattended contours led to an increased detectability of the secondary, unattended contour. If it were the case that feature based attention was involved in facilitating the target contours it would be a demonstration of a novel perceptual role for bilateral symmetry in the visual field. This enhancement was shown to be present only when the task required was performed under more difficult conditions in which the contours were less collinear (That is, the participant's detection performance improved with more complex, less coherent contours but did not occur at all when they were simpler more coherent, co-linear contours).

One issue with this explanation as a source of the enhancement of symmetry in this experiment is that studies have demonstrated that bilateral symmetry does not aid in the detection of peripheral Gaborized contours (Machilsen et al., 2009; Sassi et al., 2014, 2014). However, the presence of bilateral symmetry may be introducing a methodological confound in the form of contextual inter-contour symmetries (i.e., symmetries between adjacent contour sections between objects). These inter-object symmetries have already been linked to the detection of multiple objects (Koning & Wagemans, 2009; Baylis & Driver, 1995, 2001; van der Helm & Treder, 2009; Bertamini, 2010).

The observed enhancement could therefore be attributable to the detection of such symmetries, or lateral interactions between the adjacent contours that generate the inter-object symmetries. Hence, while it was demonstrated that the presence of bilateral symmetry played a role in the flanker facilitation effect there are a number of contextual factors that could lead to the enhancements observed in the experiment.

More generally, this experiment was used to analyse the role of the contour complexity on the detection and subsequent facilitation due to the presence of flankers. To investigate this, the change of the compactness of the contours due to the addition of orientation jitter was used to formulate a new metric called the compactness differential.

This compactness differential was then used to compare the performance of the participants across the whole range of complex shapes. The corresponding fits for both the control and same conditions demonstrated that the detection of a contour in the control condition and the flanker facilitation effect were systematically linked to the complexity of the target and the extraction of a smooth contour. A consequence of using the compactness differential was that, as it was derived from an estimation of the length of a smooth contour, it ruled out certain kinds of models of the flanker facilitation effect. In particular those models that use pre-existing attentional templates (Desimone & Duncan, 1995; Bundesen et al., 2005; Tünnermann et al., 2013; Olivers et al., 2011).

The primary reason for this was that the compactness differential was explicitly based on an estimate of a smooth contour that would require the extrapolation of global shape from local information, rather than using global information (template) to modulate local information. This distinction suggests that the local grouping processes are performing some task in which they are determining a likely smooth contour, and it is this process that is sensitive to the introduction of more global shape information from the flankers. As this result is based on the use of compactness to assess the complexity, it implies that the visual system is sensitive to compactness in the process of contour integration.

The use of a metric that combines area and contour length as independent factors may imply that the visual system is performing a form of cue-combination. This kind of perceptual mechanism has been presented in recent research in which the interior of contours (defined as regions of aligned Gabor patches) is combined with the collinear contour for optimal detection (Machilsen and Wagemans, 2014). However, as compactness can be used to a circularity it may be that it is this factor that is a critical psychophysical feature in the flanker facilitation effect. It has been demonstrated that Circularity modulates the activity of neurons in the v4 region of the visual cortex (Gallant et al., 1993, 1996; Wilkinson et al., 2000; Wilson & Wilkinson, 1998; Dumoulin & Hess, 2007). The shape level flanker facilitation may indicate a feedback process located in a higher region of the visual system (V4) in which the visual system draws additional evidence from the entire length and area of the flanker contours.

One interesting effect observed was that the comparison of the compactness differential fits between the control and same condition showed differences in detection performance for less compact shapes (higher complexity). One possible intuitive explanation, on why the extremely complex shapes in the control condition were detected in a way consistent with less complex contours, is that it may represent those cases in which the participants are detecting a smaller and less complex section of the contour. In other words, if the participant is presented with a contour of a cat, the detection performance suggests that they are detecting the body of the cat, without the legs or tail. While, in the same condition, it appears as if the visual system is performing detection based on the whole contour.

This is consistent with the flanker facilitation effect providing better direct spatial information to the detection processes and reducing noise field-contour interactions. Therefore the findings of the experiment suggest that the flanker facilitation effect is using shape level information associated with the whole flankers to determine the most likely closed contour. However, the results cannot determine how and what this sampling procedure may be. In addition to this, the stimuli organisation was a highly specific arrangement with two flanking contours. It is not therefore clear whether the flanker facilitation effect would be influenced by the number or arrangement of flanking contours.

4.5 Conclusion

The findings of this study have demonstrated that the contour integration process is sensitive to the presence of the shape information shared between the flanking and target Gaborized contours. This sensitivity is consistent with the probabilistic extraction of a smooth contour from the noise field. There was an enhancement in the facilitation to the detectability of the target contour in the presence of congruent bilateral symmetry between the contours. This indicated a potential role for symmetry due to either long range facilitation of symmetry detection, or alternatively, an effect of increasing flanker visibility thanks to the presence of either bilateral symmetry or inter-contour symmetries. In light of this, a number of questions can be asked: Does the facilitation of the target contour occur homogeneously across the visual field? What is the significance of complexity/compactness in how the visual system performs the perceptual task? How does the flanker facilitation effect vary with shape deformations in the otherwise similar flanking contours?

Chapter 5

The magnitude of the flanker facilitation effect on contour integration is modulated by changes in spatial location and numerosity of flanking contours.

5.1 Abstract

The detection of a Gaborized contour is a perceptual process in which the visual system integrates local features such as contrast and orientation into a closed contour. Previous experiments have demonstrated that the detectability of a closed contour is enhanced by the presence of flanking contours of the same shape, in conjunction with the presence of bilateral symmetry. However, the role played by contextual experimental parameters (e.g., the number of flanking contours, the presence of inter-object contour symmetries) on the facilitation effect is not known. The present study investigated the role of these factors by varying the number of flankers, and by adjusting the spatial location of flankers relative to the target contour. Shape detection (contour integration) thresholds were measured using a 2-AFC adaptive staircase procedure in which orientation noise was added to individual Gabor elements along the contour until participants were unable to detect the target contour. The target and flankers were presented in either a control condition (no flankers) or same condition (the flankers and target had the same shape). The results showed that the magnitude of the flanker facilitation effect increased with the number of flankers surrounding the target contour. Differences in facilitation were also dependent on the axis of alignment between the target and flankers, with the greatest facilitation when flankers were aligned horizontally with the target and lowest when aligned vertically. The findings are consistent with a probabilistic perceptual process that integrates available shape information into the target region, possibly involving a lateral interaction between the adjacent edges of the target and flanking contours.

5.2 Introduction

In the context of a complex environment, the visual system can detect and encode objects that are often in the presence of, partially obscured by, or overlapping other objects. To do so, the visual system identifies and integrates a wide variety of local features into the boundary corresponding to object (Wallach, 1935; Attneave, 1954). The visual system is known to respond to the local features of a small area of visual field (e.g., Local contrast, orientation and curvature) (Hubel & Wiesel, 1962, 1959;

Marcelja, 1980). These are then organised into larger configurations in a process known as contour integration. The result of this process is the perceptual formation of long, smooth contours (Wertheimer, 1923; Field et al., 1993; Barlow & Reeves, 1979; J. Beck et al., 1989, 1989; Smits et al., 1985) For a review see Loffler, 2008).

The formation of a contour is associated with the detection of a target in a delimited region. However, at a local level there are a large number of findings that have demonstrated the importance of features presented contextually in a wider region of the visual field. For instance, the presence of flankers with supra-threshold contrast can facilitate the detectability of low contrast Gabor patches in a process known as collinear flanker facilitation (Polat & Sagi, 1993; Adini et al., 1997; Bonneh & Sagi, 1999; Cass & Spehar, 2005; Chen & Tyler, 2001; Freeman et al., 2001; Huang & Hess, 2007; Mizobe et al., 2001; Katkov & Sagi, 2010; Polat & Tyler, 1999; Sterkin et al., 2008; Woods et al., 2002; Zenger & Sagi, 1996)

A number of inhibitory processes that suppress the detection of a target have also been observed. One such perceptual effect, surround suppression, occurs when a target is paired with flankers that compete for a single receptive field while having similar contrast/orientation features with the target. This competition has been shown to decrease the detectability of a central target (Tadin et al., 2003; Born, 2000; Pack et al., 2005; Churan et al., 2009; Spillmann, 1994; Troncoso et al., 2007; Petrov et al., 2007). A similar inhibitory effect also occurs in a suppressive process known as crowding (Bouma, 1970; Stuart & Burian, 1962; Pelli & Tillman, 2008; Toet & Levi, 1992; Levi, 2008; Levi et al., 2002; Parkes et al., 2001; Pelli et al., 2004). On a more global level, overall changes in viewpoint can have an impact on the shape of an object projected onto a retina. Such changes in the viewpoint have been shown to affect how the visual system performs detection and recognition, with enhanced processing for canonical and familiar viewpoints (Tarr & Pinker, 1989; Jolicoeur & Milliken, 1989; Moses et al., 1996; Vetter & Poggio, 1994; Palmer et al., 1981; Koenderink & Van doorn, 1979; Tarr & Kriegman, 2001).

The relative positions of objects that arise due to changes in viewpoint can introduce contextual regularities in the scene. These are, by themselves, important to the visual system. For instance, when two objects are adjacent to each other and the curvature of the boundary of objects is similar, it can introduce symmetries between the objects. The visual system is known to be sensitive to such inter-object symmetries, which have been linked to the detection of multiple objects (Koning & Wagemans, 2009; Baylis & Driver, 1995, 2001; van der Helm & Treder, 2009; Bertamini, 2010). An example of an inter-object symmetry is presented in 5.1.

A number of further contextual effects that can influence the capacity for detection involving both the presence of multiple objects and the allocation of attention in a scene. For instance, limitations in how many objects can be attended to simultaneously can lead to the disruption of the detection of an object that take up a large portion of the visual field and contain substantial motion, shape and colour cues (Levin & Simons, 1997; Simons & Chabris, 1999). In turn, the latency for the detection of a target is modulated by the presence of 'redundant' cues. For example, an observer more quickly detects a target when other additional cues compared with the detection of the target (Todd, 1912; Miller, 1982; Krummenacher et al., 2001, 2002a; Ben-David & Algom, 2009; Toellner et al., 2011).

5.2.1 The flanker facilitation of a Gaborized closed contour.

In recent research, a number of effects have been observed in which a closed Gaborized contour can be modulated by the presence of additional contours across the visual field (see Chapters 3 and 4, p 51 and 94; Stojanoski & Niemeier, 2007). In the former studies, a global impact of flanking contours on the detectability of a central Gaborized contour has been shown, with observers more readily able to detect a target contour when it is presented with flankers with the same underlying shape (see Chapter 3 and 4).

A secondary enhancement was observed that appeared to be modulated by the presence a shared, bilateral symmetry in both the target and flanker contours. In other words, the overall magnitude of the flanker facilitation effect was shown to be greatest when the target and flanking contours were both the same shape, and that shape was bilaterally symmetric. One potentially problematic issue in linking bilateral symmetry and common shape to modulation of the facilitation effect, is the stimuli used in the previous studies potentially introduced specific inter-object contextual relationships. Therefore, there were two important unaccounted factors in the previous experiments. Firstly, the flanker facilitation effect was only identified using a limited number of flanking contours, so it was not clear how numerosity of flankers contributed to the effect, and, secondly, the enhancement may have been due the target contour creating contextual inter-object contour symmetries between the target and flanker.

The present experiment investigates these two inter-related, spatial factors in the contour integration of a closed Gaborized contour.

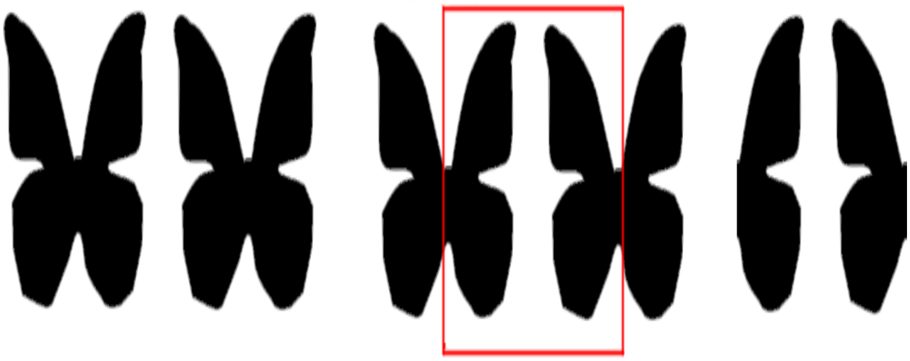

Figure 5.1: **The presence of bilateral symmetry in adjacent contours introduces inter-object symmetries.**

Inter-object symmetries have been shown to be as detectable as within-object symmetries under certain experiment conditions. The enhanced flanker facilitation effect may be due to lateral interactions that arise when symmetries are present. In the case of the butterflies presented side−by−side. The symmetries arise between the two contours (Red box and left images)

5.2.2 Number of flanking contours surrounding the target contour.

The previous experiment (see Chapter 4, p .95) proposed that the perceptual mechanism may be a probabilistic procedure in which the shape information present in the flanking contours directly modulated the contour integration process. Hence, the increase in number of flankers would be expected to provide increasing evidence that would allow more accurate detection of the target contour.

The initial set of experiments contained only 2 flankers that are equidistantly arranged on either side of the central target contour. To perform the central detection task the observers were required to focus their attention on the central target region and not look at either flanker. However, it is not clear what role the allocation of attention plays in the overall observations. For instance, the increased detectability could be related to how the visual system is attempting to gather information to perform the task. Alternatively, owing to the overall similarity of the flanking and target contours, it is conceivable that they trigger common perceptual mechanisms that share a single set of neuronal responses.

A number of observations have been made that have shown that attention is constrained by the numerosity of objects that can be attended to at any given moment, with the visual system being able to accommodate around 4-5 objects at once (Yarbus, 1961; Pashler, 1994; Evans et al., 2011; Posner et al., 1980; Maxfield, 1997; Baylis & Driver, 1989, 1992; Duncan & NimmoSmith, 1996; Rossi & Paradiso, 1995; Simons & Chabris, 1999). While a large number of flanking contours could contribute more strongly to the facilitation, attentional processes might only draw from a smaller set size. Hence, the visual system will have a decreasing capacity to draw information from the flanking contours if attention plays a role in the flanker facilitation effect.

The present experiment investigates these various possibilities by placing an increasing number of flanking contours (up to 4 additional flankers) in the region surrounding the target contour. Moreover, the relative alignment of the flankers and target were also varied to explore the potential role of inter-object symmetries.

5.2.3 Alignment of flanking and target contours.

The findings of the previous experiment indicated that flanker facilitation effect was enhanced when the shape and presence of bilateral symmetry in the flanking contours surrounding the target contour (see Chapter 3 and 4, p.51 and 94). However, this enhancement could be explained in a number of ways. Firstly, that the bilateral symmetry that was common to the flankers and target increased the visibility of the shape level information that the visual system was collecting for the flanker facilitation effect. Secondly, that the presence of bilateral symmetry was enhancing the detection of other symmetries in the visual field and that this was a second novel mechanism uncovered by the experiment. Finally, that there were contextual enhancements to the detectability of the target contour due to the edges of the adjacent contours creating inter-object symmetries.

The possibility that the bilateral symmetry was enhancing the flanker facilitation effect directly was consistent with previous research in which a common feature between a central attended and peripheral unattended target facilitated the detectability of the latter (Stojanoski & Niemeier, 2007). This effect was observed only when the task itself was more difficult to perform. In other words, it was only when the visual system was presented with a need for further resources to resolve ambiguities in the visual field did the visual system make use of common features to modulate the visibility of peripheral contours. One issue with this explanation was that Sassi et al (2014) have demonstrated that bilateral symmetry did not facilitate the detectability of Gaborized contours presented by themselves in peripheral vision. Therefore, should this be the case the enhancement may itself be a novel demonstration of a novel additional psychophysical effect of bilateral symmetry.

Under this light the flanker facilitation effect may be a multi-step perceptual process in which the visual system (A) finds the detection task too difficult to perform, (B) extends the region of the visual field from which evidence is accumulated to compensate for this difficulty (C) which activates perceptual processes involving bilateral symmetry in the flanking contours, enhancing the amount of visual information being accepted from flanking contours. This would result in an increase in available relevant information and therefore a higher detectability for the target contour. A plausible alternative to this explanation is that, due to the stimuli consisting of contours that were equidistantly aligned along one plane, there may be inter-object effects such as those observed when symmetries occur between objects (Koning & Wagemans, 2009; Baylis & Driver, 1995, 2001; van der Helm & Treder, 2009; Bertamini, 2010). Hence, the enhancement may be a simple, lateral interaction in which the visual system is more sensitive to fine-tuned spatial information across the target contour. This greater sensitivity may then result in a larger magnitude of flanker facilitation.

To distinguish between these possibilities the present experiment investigates the role of position and alignment of the flanking contours in two ways: Firstly, the magnitude of the flanker facilitation effect is investigated as a function of the number of flanking contours in two groups of locations (e.g., adjacent and diagonal to the target contour). Secondly, the magnitude of the flanker facilitation effect when two flanking contours are both presented in different locations on the horizontal and vertical plane. The conditions that correspond to either direct alignment (edges of the contours are adjacent), some misalignment (one half of the upper/lower section of the flanking contour is aligned with opposite section of the target contour) or completely misaligned (no alignment between corresponding edges of the contours). The experiments used contours that had bilateral symmetry. Hence, if there are lateral interactions between the adjacent edges of contours the alignment of the contours along the vertical or horizontal plane should contain a larger magnitude of facilitation than the less aligned conditions.

5.2.4 Experimental summary

The present experiments investigated the role of two contextual factors – the number of flankers around the target contour and the alignment of the flanking contours with respect to the target contours. The experiments consisted of detecting a Gaborized target contour embedded in a random Gabor noise field. The detectability of such target contours was determined by a 2-AFC adaptive staircase procedure. Detection thresholds were defined as the maximum amount of orientation noise that could be added to the contour before it became undetectable. Therefore higher levels of noise indicated more enhanced levels of detectability.

Experiment 1 investigated the role of flanker numerosity in either a cardinal arrangement (Experiment 1a) or a diagonal arrangement (Experiment 1b) relative to the target contour. Experiment 2 investigated the role of differences in the relative alignment of the flanking and target contours along the vertical and horizontal planes.

5.3 Experiment 1: Number of flankers surrounding target contour

5.3.1 Methodology

Participants

Experiment 1a was performed by 18 participants who were paid volunteers (£5 for each hour). 16 were undergraduate students and 2 were postgraduate students. 13 of the participants were female. 9 of the participants had performed experiments for the previous experiments (see Chapter 3 and 4, p.51 and 94). 1 participant was unable to perform the task and their data was discarded. The participants were in the age range of 17 to 50.

Experiment 1b was performed by 15 undergraduate participants who were paid volunteers (£5 for each hour). 10 of the participants were female. All of the participants had performed experiments for the previous experiments (see Chapter 3 and 4). The participants were in the age range of 17 to 30.

Two breaks were provided during the session approximately 1/3 and 2/3 of the way through the experiment and the duration was determined by the participant. Each participant performed one session of 1 hour. All observers had normal or corrected-to-normal vision. Ethics was granted by the St Andrews University Teaching and Research Ethics Committee (UTREC - Ethics reference number: PS7638), and participants received a payment for participation for the experiment.

Apparatus

Experiments were presented on a Dell 2407WFP LCD display with a resolution of 1920x1200 with a refresh rate of 60 Hz. The viewing distance was 57 cm. Participants viewed the screen from a chin/head rest. The experiment was implemented using Matlab (Mathworks, Inc) using the psychophysics toolbox utilities (Brainard, 1997) Statistics were performed in R (R Development Core Team, 2008) and presented using Gnuplot (Williams and Kelley, 2011.)

Stimuli

The stimuli were created using the Grouping Elements Rendering Toolbox (Demeyer & Machilsen, 2012) based on Matlab programming language. The staircase procedure used to present the stimuli for each trial was run using the Palamedes Toolbox (Prins & Kingdom, 2001).

The stimuli consisted of two components: A set of sine waves windowed by a Gaussian envelope, known as a Gabor patch, and a generating shape combined with a set of Gabor patches to generate the stimuli presented to the observers. The Gabor patches consisted of a sine wave luminance profile of frequency 2 cycles/deg and the 2-dimensional Gaussian envelope with a Gaussian standard deviation (sigma value) of 3 pixels. The phase of each Gabor patch was randomised by 90 degrees.

Figure 5.2: **Shapes used to generate target and flanker Gaborized contours.** The shapes were generated using outlines of everyday objects. The shapes consisted of bilaterally symmetric, familiar shapes.

The panel was primarily populated with a field of randomly positioned, non-overlapping, randomly oriented Gabor patches (referred to as the noise field). The average initial minimum spacing between Gabor patches in the noise field was around 16.5px.

To create the target contours, a set of generating shapes was combined with a number of Gabor patches. The generating shapes are presented in Figure 5.2.

A set of approximately 21 Gabor patches was placed at randomised intervals along the perimeter of the generating shape (Figure 3.2). The width of these intervals was randomised. The maximum width to which subsequent Gabor patches could be positioned was a single wavelength. Inspections were made of the subsequent Gaborized contours and minor adjustments (+/- 2 Gabor patches) were made if the resultant contour lacked corners or extrema. The orientation of these individual Gabor patches corresponded with the local orientation of the underlying generating shape

The stimuli consisted of a grey rectangular panel placed on an otherwise black screen. The panel dimensions were 14 by 14 degrees on the monitor screen from the position of the chin rest (see Figure 5.3). The panel was populated with a field of randomly positioned, non-overlapping, randomly oriented Gabor patches (referred to as the noise field). The Gaborized contours were then embedded in the noise field (Figure 3.4) so that there was no overlap with the randomly orientated noise Gabor patches. The Gaborized flanker contours were embedded in a Gabor field whose Gabor patches were aligned vertically. This was done based on the previous study in order to maintain visibility for more complex generating shapes (see Chapter 3).

The combination of Gaborized contours and the noise field introduced possible variations in the density of the overall panel of Gabor gratings. To assess the presence of probabilistically significant density differences, and to subsequently adjust the relative locations of the set of Gabor patches, a method native to the stimuli generating program, G.E.R.T, was used. This employed a Voroni tessellation to isolate the immediate area surrounding each Gabor patch and trace it as a polygon. The surface areas for the polygons were computed and compared across both the noise field and the embedded contours to determine that the surface areas were reasonably uniform across the whole stimuli.

Experimental conditions were created by pairing a target contour in the centre of the presentation region with a number of flanking contours. The experimental conditions consisted of a target contour paired with 0, 1, 2, 3, or 4 flanking contours with the same shape. These flanking contours were presented in the adjacent locations above/below and left/right of the target contour in Experiment 1a. In experiment 2a the flanking contours were presented in one of the four corners (diagonal) of the presentation panel. These are shown in Figure 5.4.

For each condition there were a number of possible combinations of locations and flanking contours (I.e., a single flanker presented could be in one of four positions around the target contour. During the trials the possible locations were randomised between the possible combinations. For any given staircase the participant was presented a single number of flanking contours (e.g., 0,1,2,3 or 4) that were randomly arranged spatially relative to target contour.

The Detectability of the target contour was altered by adding orientation noise jitter to the individual Gabors making up the contour (Figure 3.5). The amount of orientation noise jitter added across the set of Gabor patches was sampled from a normal distribution. The maximum value such orientation jitter could take was the range of 90 to -90 degrees adjustment from alignment. In these experiment the results are reported as the magnitude values (e.g., the range of 90 to -90 corresponds to a magnitude of 180 degrees). For these experiments 40 degrees of noise jitter represented a highly visible contour with a low level of orientational noise jitter, while 120 degrees of noise jitter represented a contour with low visibility with a high level of orientational noise jitter.

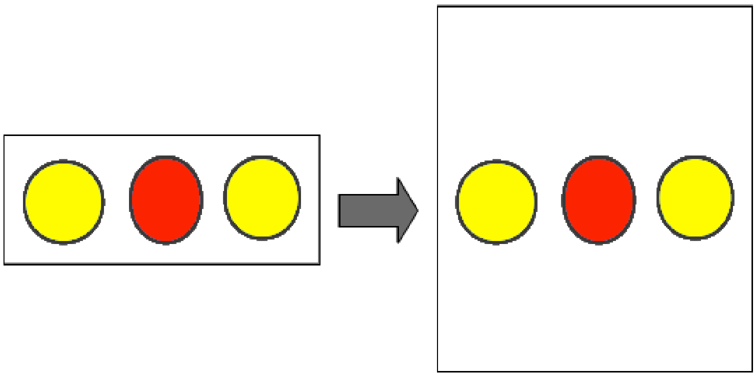

Figure 5.3: **The region surrounding the target contour containing flanking contours in comparison to that used in previous experiments.**
In previous experiments the flankers were placed in a region of 4.5 by 14 arc degrees. To accommodate for the increase in flanker number and changes in location the region was increased to 14 by 14 arc degrees

5.4 Procedure

Each trial consisted of two sequential stimulus presentations with both a target-present panel and a target-absent panel. In the target-present panel the target was displayed centered horizontally. The target absent panel was identical to the target present panel except that there was no target contour present. In order to prevent any gross differences in perceived density of the two types of panels the average

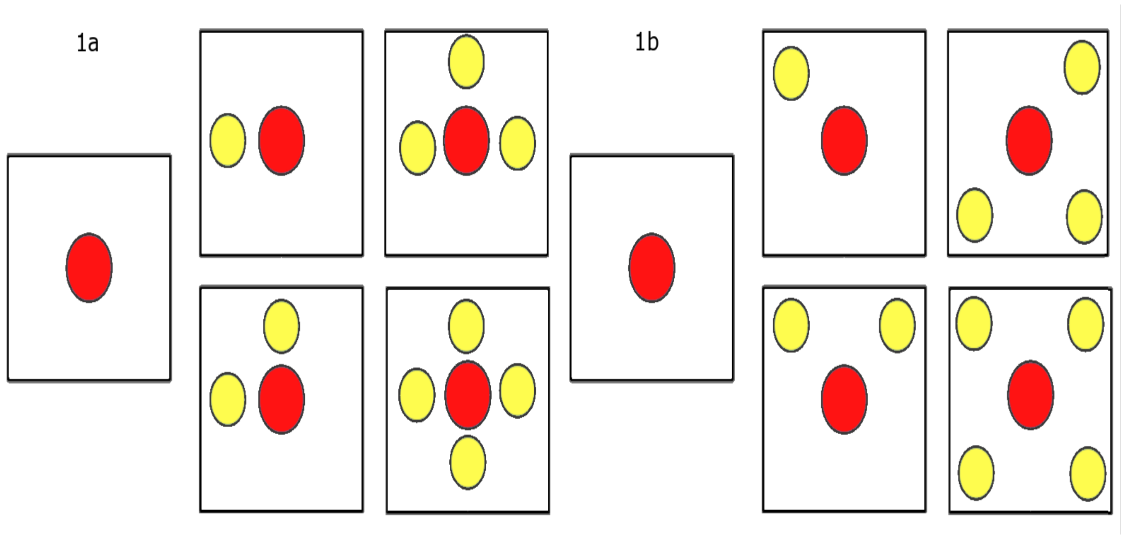

Figure 5.4: **Conditions presented to examine the role of numerosity of flanking contours on target detectability.**
The conditions presented consisted of a target and a possible range of flanking contours. Two experiments were performed in which 0, 1, 2, 3 or 4 flankers were presented.

density of the target absent panels was generated by matching to the value of the target present condition. There were therefore equal numbers of flankers in both panels. The density value was further used to create a set of 5 inter-trial display panels for each set of presentation panels. These inter-trial display panels contained no contour information as they contained randomly positioned and orientated Gabor patches only.

The sequence of stimulus presentation (Figure 1.8) involved an initial fixation cross at the center of the main display panel (800 ms), followed by a fixation cross appearing at the left half of the overall panel. This was followed by the presentation of either a target-present or target absent stimulus panel for 200 ms. After this time, a fixation cross appeared at the opposite location (Right panel) and was followed by either the target-absent or target-present panel depending on what was previously shown. A circle was presented with no fixed duration in which the participant was asked to respond if a contour was present in either the left or right panel. Once a

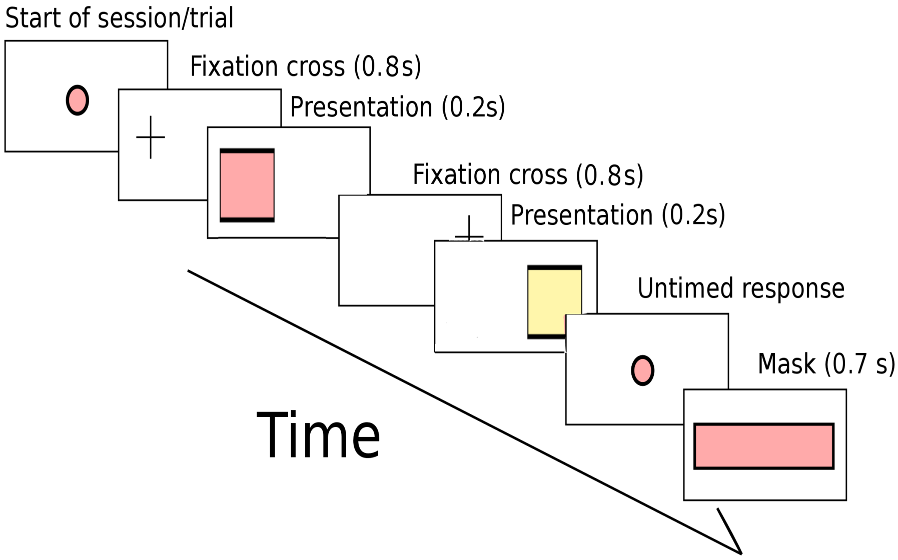

Figure 5.5: **The time course of a single trial.**
The stimulus consisted of two presentations, one of which contained the target object. The presentations were presented in the left (red) and then right side (yellow) of the monitor from trial to trial. Each presentation consisted of an initial fixation cross that directed the observer's attention to the target location, this was followed by one of the stimulus frames. Each stimulus frame was either a target-absent or a target-present image. Once the two stimulus frames were presented, a red circle appeared that prompted the subject to indicate in which stimulus frame (first or second) they saw a target object, this circle remained until the observer made a response. Finally an inter-trial display image was presented.

response was recorded an inter-trial display was presented for 700 ms and a central red circle was displayed (200 ms) to indicate the beginning of a new trial.

The initial presentation panel presented for each contour consisted of Gabor gratings aligned to the underlying generating shape. The initial level of noise jitter for each staircase was at 12 degrees of noise. That is, the contour was extremely visible and detectable to all participants.

The degree of orientation noise was varied according to participant responses using a weighted 1-up 1-down staircase procedure targeting approximately a detection threshold of 67 percent (Kaernbach, 1991). This rule was adopted after an initial 3 trials. The step size in the initial 3 trials was 16 degrees of noise. This large step size was intended to reduce the number of steps required to approach the detection threshold level. After the first 3 trials, step size was reduced to 4 degrees. If the participant was incorrect at the lowest level of noise the level of noise remained the same during the first three trials.

To extract the detection threshold, the staircase procedure varied the magnitude of the added orientational noise jitter until the participant was no longer able to detect the shape (Figure 5.5). Each staircase was terminated after 15 reversals occurred for the individual contour and the threshold was calculated by taking the mean value over which the last 10 reversals took place. In circumstances where less than 15 reversals occurred by the end of 50 trials the individual staircase was terminated. If the staircase resulted in less than 9 reversals the data was discarded.

The detection thresholds are presented in the reciprocal detectability values corresponding to the absolute magnitude of orientation noise jitter added per trial. Therefore a decrease in the detection threshold corresponds to an increase in the detectability of the shape under greater degrees of additional noise.

A number of participants could not perform the task for all contour types (that is, for complex contours such as the cat, their performance was around the lowest level of additional noise). Additionally, a number of contours staircases over-shot the detection threshold and did not return in the allocated number of trials. Two limits corresponding to detectability values of 30 and 160 were chosen and data that was above or below these points was removed.

5.4.1 Results

The mean detection threshold was determined by averaging over all target contour shapes with the same number of flankers. The mean values averaging across all observers for Experiment 1 are shown in the bar plot in figure 5.6.

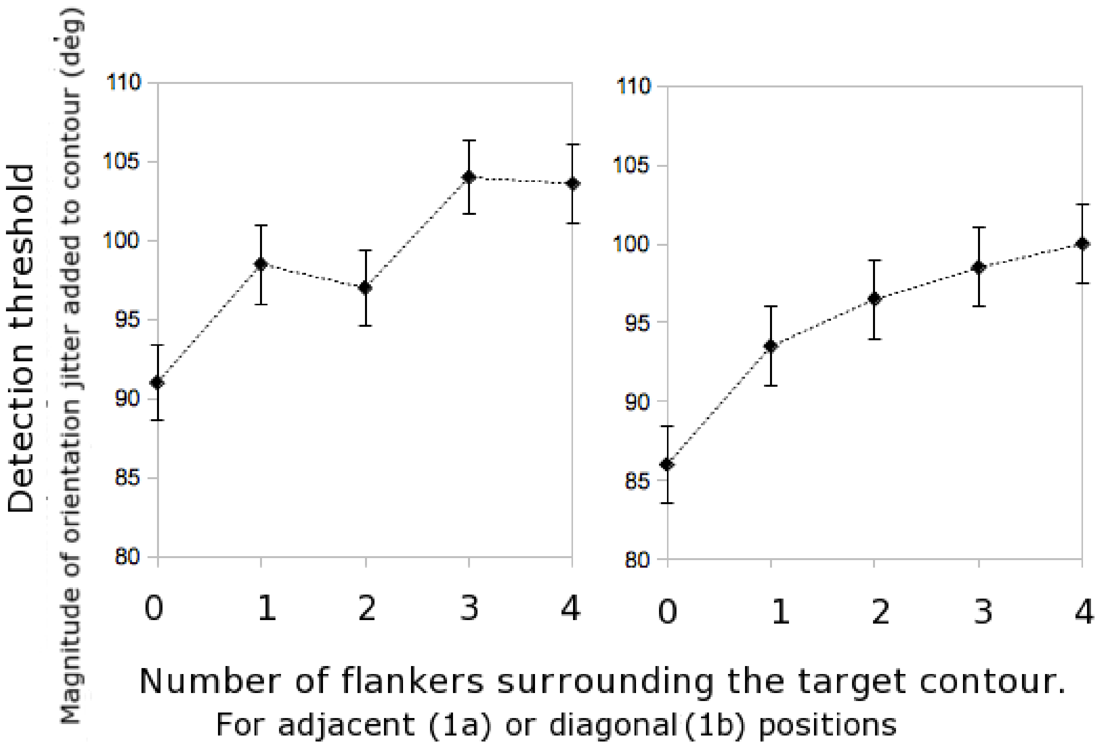

Figure 5.6: **The mean detection thresholds of the target contour as a function of the numerosity of flankers.**

The detectability thresholds are presented as a function of the numerosity of flanking contours. These conditions were tested in either adjacent (left graph) or diagonal (right graph) locations with respect to the target contour. The plotted data are the magnitude of orientation jitter added to a central target contour at a detection threshold of approximately 70 percent proportion correct averaged over all participants (n=18/n=15). Error bars represent the standard error of the mean.

In both experiments 1a and 1b the lowest over all magnitude for the detectability of the target contour was when the target contour was presented without any flanking contours. In turn the general increase in the number of flanking contours corresponded to an increase in the detectability of the target contour. There were a number of important distinctions in the behaviour between conditions where the flankers were placed in the cardinal positions (above/below, left/right) and those where they were placed on the diagonal.

The general increase was non-monotonic for the increase in the flanker number when they were presented in the cardinal (vertical/horizontal) arrangement with respect to the target contour (Experiment 1a). In comparison, the increase was monotonic when the flankers were in the diagonal positions. In addition, the overall magnitude increase associated with the addition of a single flanker decreased and appears to start plateauing at 4 flanking contours. This suggested that addition of more flankers would have a diminishing effect on facilitation. For experiment 1a the addition of flankers had a significant effect on detectability ($F(4,72)=4.9$, $p < 0.01$). The planned pairwise comparisons using a Tukey test corresponded to the non-linear effects apparent across the data with a significant increase in detectability relative to control condition for single ($p=0.04$), three ($p<0.001$) and four ($p<0.001$) flankers. The addition of two flankers did not have a corresponding significant difference compared to the control ($p=0.34$).

One possibility for this variability in the mean values may have been that the variation for the underlying data may not be homogenous across the conditions, equally likely that the individual conditions were distributed in a non-normal way. A Levene′s Test for the equality of variance demonstrated that the homogeneity of the variance was equivalent for each condition (Test statistic = 0.92, $p = 0.454$). While Shapiro-wilk tests indicated that the control ($W=0.9584$, $p=0.24$), single ($W=0.9837$, $p = 0.57$), two ($W=0.9823$, $p = 0.4875$), three ($W=0.9812$, $p = 0.3961$), and four ($W=0.9861$, $p = 0.2393$) satisfied normality. Similarly, the increase in detectability with addition of flankers in experiment 1b was also significant. ($F(4, 56)=3.194$, $p < 0.05$). The planned pairwise comparisons using a Tukey test revealed that compared to the baseline control containing no flankers the addition of a single ($p<0.05$), two, ($p<0.05$), three ($p<0.01$) and four ($p<0.001$) flankers were significantly higher than the control.

The difference between the two experiments indicated that it was likely that the differences in the significance in the conditions was due to the contextual differences in the experiment, that is, the flanker facilitation effect was sensitive to the spatial organisation of the contours presented to the observer.

5.5 Experiment 2 - Alignment of target contour and flankers.

Experiment 2 investigated the effects of relative spatial position between the target-contour and flankers. The flanker and target contour's alignment was adjusted along both the (A) vertical and (B) horizontal axis. Bilateral symmetry was present in the contours for all alignment conditions. Any differences in the magnitude of the flanker facilitation effect with respect to alignment therefore is hypothesised to indicate a role for contextual inter-object contour effects.

5.5.1 Methodology

Participants

Experiment 1a was performed by 12 participants who were paid volunteers (£5 for each hour). 10 were undergraduate students and 2 were postgraduate students. 13 of the participants were female. 9 of the participants had performed experiments for the previous experiments (see Chapter 3 and 4, p.51 and 94). 1 participant was unable to perform the task and their data was discarded. The participants were in the age range of 17 to 50.

Experiment 1b was performed by 9 undergraduate participants who were paid volunteers (£5 for each hour). 7 of the participants were female. All of the participants had performed experiments for the previous experiments (see Chapter 3 and 4). The participants were in the age range of 17 to 30.

Two breaks were provided during the session approximately 1/3 and 2/3 of the way through the experiment and the duration was determined by the participant. Each participant performed one session of 1 hour. All observers had normal or corrected-to-normal vision. Ethics was granted by the St Andrews University Teaching and Research Ethics Committee (UTREC), and participants received a payment for participation for the experiment.

Apparatus

The apparatus was identical to that in experiment 1.

Stimuli

The presentation panel (Size of panel, Size of contours and Gabor patches) were identical to that in experiment 1. The spatial position in which the flankers were presented was in 1 of 5 positions along either a vertical (above/below) or horizontal (left/right) arrangement. Alignment was varied by moving the flanker contours along perpendicular to this arrangement (I.e In a vertical arrangement the contours were moved left/right of their initial positions). These are presented in Figure 5.7. Three conditions were created by measuring the detection thresholds when the flankers were adjacent to the target, partially misalignment in which the edges of the contours overlapped, and fully misaligned in which the flankers were presented in diagonally with respect to the target contour.

Procedure

The procedure was identical to that in experiment 1. The horizontal and vertical flanker conditions were tested in separate experimental sessions. The purpose of this was to decrease the possibility that participants were having to readjust their focus of attention from a horizontally to a vertically orientated window.

5.5.2 Results

Figure 5.8 and Figure 5.9 show the mean detection thresholds in which the flankers were in a Horizontal arrangement: alignment with respect to the horizontal axis (flankers to left or right or target and moved up and down(Figure 5.8)) and in a

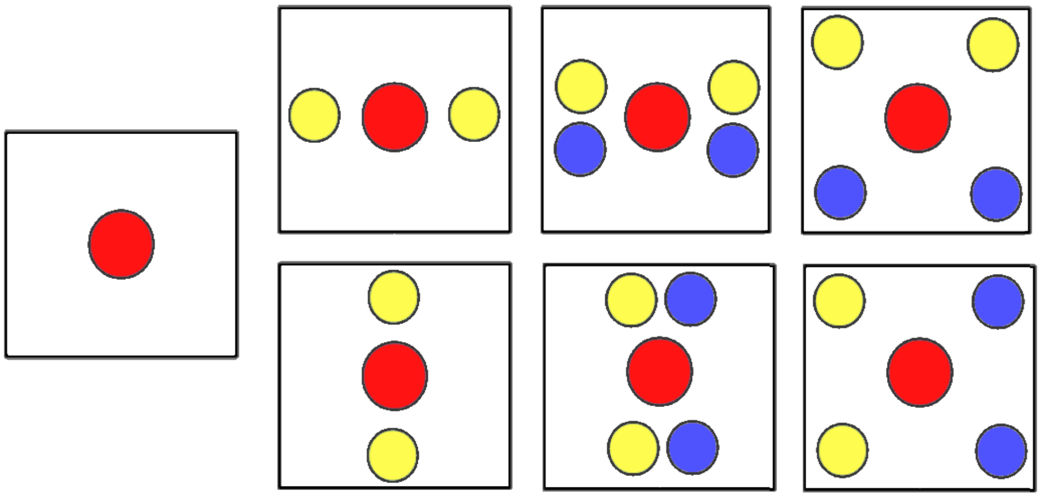

Figure 5.7: **The conditions used to examine the role of relative flanker position on target detectability.**

A control condition was presented with either a horizontal (upper three conditions) or vertical (lower three conditions) arrangement of flankers. The three levels of alignment were created by decreasing the alignment along either the vertical or horizontal axis respectively. These three conditions were aligned, partially misaligned and fully misaligned. The partially and fully misaligned conditions consisted of two positions (yellow and blue circles) either above/below or left/right respectively.

Vertical arrangement: alignment with respect to vertical axis (flankers above and below target and moved left and right (Figure 5.9))

For the horizontal arrangement the greatest magnitude of facilitation, relative to the control, was observed when the flankers were aligned on either side of the target contour. The detectability of the target contour was symmetric with respect to target-flanker alignment. In other words, the detectability of the partially and fully misaligned conditions were similar to each other regardless of whether they were located above or below the target, the data was therefore collapsed across them. There was a statistically significant difference in facilitation for changes in the target and flanker alignment along the vertical plane as revealed by a main effect ($F(3,33)=6.124$, $p<0.01$). In comparison, for the vertical arrangement, there

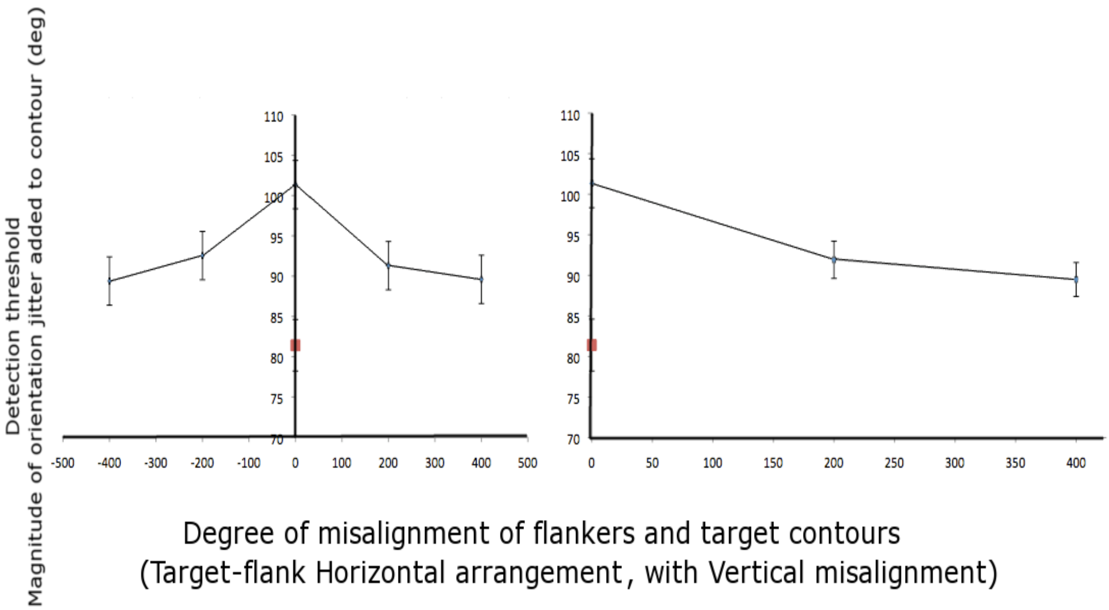

Figure 5.8: **the mean detection thresholds of the target contour as a function of flanker alignment in the horizontal arrangement.**
The detection thresholds are presented for each of the target-flanker conditions. The two graphs contain the overall data (left) for positions of the flankers (above and below flanking positions separately), the combined data (right) for the alignment only (above and below flanking positions combined). The plotted data are the magnitude of orientation jitter added to a central target contour at a detection threshold of approximately 70 percent proportion correct averaged over all participants (n=14). Error bars represent the standard error of the mean.

was a greater degree of variability across the partially and fully misaligned conditions when the flankers were located either to the left or right of the target contour and no apparent facilitation in the alignment conditions. There was no statistically significant difference in facilitation for changes in the target and flanker alignment along the vertical axis ($F(3,24)=2.04$, $p = 0.135$).

For adjustments in the horizontal stimulus arrangement planned pairwise comparisons using a Tukey test revealed that the difference between the partially aligned ($p<0.05$), fully misaligned ($p<0.001$) and aligned ($p<0.001$) flankers were significantly higher than the control condition. However, the aligned condition showed a

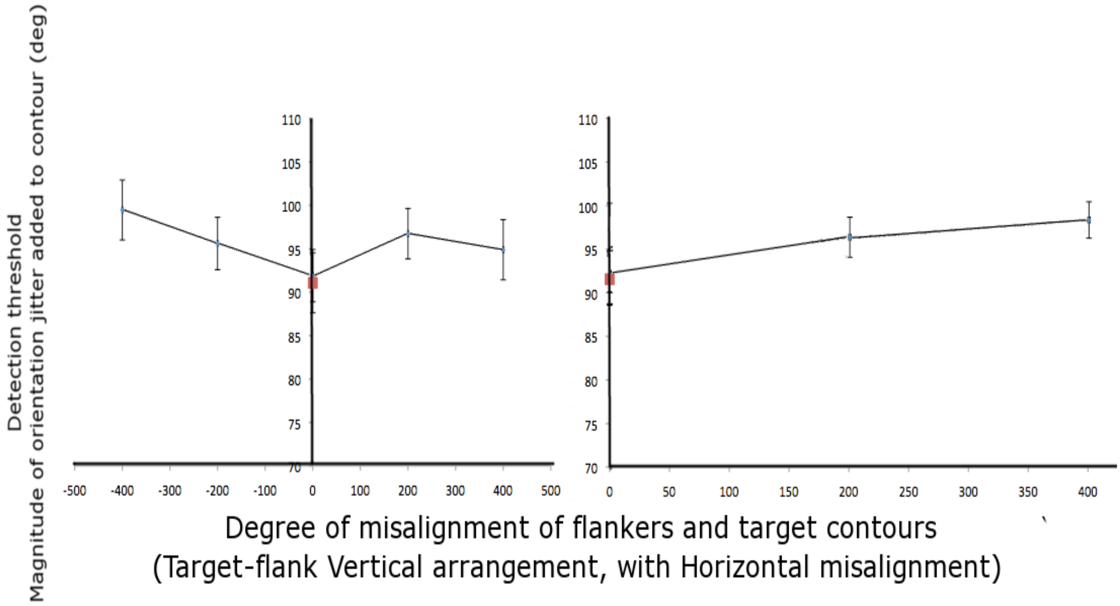

Figure 5.9: **The mean detection thresholds of the target contour as a function of flanker alignment in the vertical arrangement**
The detection thresholds are presented for each of the target-flanker conditions. The two graphs contain the overall data (left) for positions of the flankers (right and left flanking positions separately), the combined data (right) for the alignment only (right and left flanking positions combined). The plotted data are the magnitude of orientation jitter added to a central target contour at a detection threshold of approximately 70 percent proportion correct averaged over all participants (n=14). Error bars represent the standard error of the mean.

greater effect on detectability when compared to the partially misaligned ($p<0.01$) and misaligned ($p<0.01$). While the differences between the partially misaligned and misaligned conditions were not significant ($p=0.73$). The data indicates that the primary effect on facilitation is associated with direct alignment along the horizontal axis. The resulting observations indicated that the magnitude of the flanker facilitation when they were equidistant and adjacent along the horizontal axis. In contrast, no facilitation was observer for contour adjacencies above and below target (vertical stimulus arrangement).

5.5.3 Summary

An overall increase in the magnitude of the flanker facilitation effect was observed when the flankers were aligned along the horizontal plane. As the alignment was decreased along this axis the magnitude of the flanker facilitation decreased but was still present in the unaligned condition. Conversely, the magnitude of flanker facilitation was lower in the vertical alignment condition. The findings of this experiment are plausibly consistent with a role for contextual inter-object contour features instead of or in addition to the presence of in-object contour symmetries. An unexpected finding was that the flanker facilitation effects appears to depend on whether the flankers are aligned along the vertical or horizontal axis This finding suggested a potential explanation for the non-linear effects observed in the previous experiment.

5.6 General Discussion

The general focus of this study was to investigate the role of contextual factors that may have modulated the flanker facilitation effect observed in two previous studies (see Chapter 3, p.51). The stimuli presented during these experiments contained either 0 or 2 flanking contours. Furthermore, these contours were only presented horizontally adjacent to the target which limits the generalizability of the results.

The purpose of experiment 1 was to determine whether the flanker facilitation effect was indeed sensitive to the increase in flanker numerosity. For contours presented vertically and horizontally adjacent to the target contour the number of flankers was shown to increase the detectability of the target contour. However, the relationship was non-monotonic and did not conform to expectations based on previous experiments. The conditions were then presented with the positions of the flanking contours placed in the diagonal corners of the presentation panel. Here the overall enhancement to the flanker facilitation effect monotonically increased with each additional flanking contour. This increase appeared to asymptote with greater numbers of flankers, with a smaller contribution of each additional flanker.

Experiment 2 was conducted to examine the role of lateral, inter-object contour effects that arise due to alignment between the flankers and target. This has implications for previous findings that linked the presence of bilateral symmetry to the enhancement of the flanker facilitation effect (see Chapter 3 and 4, p.51 and 94). The magnitude of the facilitation was shown to depend on the spatial alignment of the target and flankers. While there was facilitation in all conditions, the highest facilitation occurred for horizontal alignment, with decreasing facilitation for increasing levels of misalignment. However, there were differences along the cardinal axis with the alignment along the horizontal axis facilitating the detectability more than the alignment along the vertical axis. Taken together, the findings further characterised the flanker facilitation effect by indicating the role of spatial and contextual factors that modulated the overall magnitude of the facilitation. The implication of these results and the previous ones (see Chapter 3) is that the perceptual organisation of the Gabor patches into a smooth closed contour is better when there are more sources of spatial information (e.g., increased flanker number) and that it is greater again when the flanking contours are presented horizontally adjacent.

There are three novel findings in these experiments:

(A) The magnitude of the flanker facilitation effect is in itself not uniform and can be modulated by contextual factors such as numerosity and relative alignment.

(B) The effect of increasing the number of flankers on the magnitude of facilitation is non-linear and each additional flanker does not cause equivalent enhance.

(C) The facilitatory role of flankers depends on the cardinal axis along which the flankers and target are aligned.

This asymptotic behaviour due to the number of flanking contours (B) implies that the flanker facilitation effect is constrained by a third, unknown process. (e.g., one modulated by spatial attention or some other sampling process). In turn, the implications of the effects of alignment (C) is that the flanker facilitation effect could also be driven by extraneous factors, such as inter-object contour symmetries, that depend specifically on the nature of the relative alignment of the target object and flankers.

5.6.1 The sampling of shape information from increasing numbers of flanking contours.

Overall an enhanced detectability for increasing the number of flankers was observed. However, the magnitude of this enhancement decreased when more than 3 to 4 contours were present. One possibility that may explain this behaviour is that there are a variety of known limitations to attention that may provide constraints to the flanker facilitation effect. For instance, the attentional spotlight has been shown to be limited to maintaining a set size of 4-5 with complex inhibition effects associated with increasing the set size beyond this limit (Pylyshyn & Storm, 1988; Yantis, 1992; Yarbus, 1961; Pashler, 1994; Evans et al., 2011; Posner et al., 1980; Maxfield, 1997; Baylis & Driver, 1989, 1992; Duncan & NimmoSmith, 1996; Rossi & Paradiso, 1995; Simons & Chabris, 1999).Hence, the asymptotic behaviour may indicate that the attentional processes are required to sample information from the flanking contours.

However, equally plausible is that, if the visual system is determining the most likely smooth contour in the target region (see Chapter 4, p.94), this plateau in the magnitude may be due to an optimal value in the amount of evidence that the visual system needs to perform the task. In other words, as the number of flanking contours is increased in the surrounding flanking region the visual system extracts the maximum amount of information available from 2 to 3 contours and the 4th contour provides much reduced information about the target contour. For instance, if the visual system was encoding a mean value of some psychophysical feature (known as ensemble encoding, Alvarez, 2011) then it may be that an accurate estimate of the mean may be extrapolated by the visual system using around 2 flankers, and any more than this may fine-tune the estimate of the mean shape but not adjust it in any substantive way. One possibility is that the visual system is encoding a parameter such as compactness (see Chapter 3 and 4, p.51 and 94) or aspect-ratio in a similar way to previous demonstrations of encodings of the mean size (Ariely, 2001; Chong & Treisman, 2003), and orientation (Dakin & Watt, 1997; Chong & Treisman, 2003; Parkes et al., 2001; Alvarez & Oliva, 2008) of objects.

5.6.2 The enhancement of target contour detectability with differences in alignment.

In previous experiments the flanker facilitation effect was shown to be enhanced when the flanking contours were both the same shape, as well as containing bilateral symmetry (see Chapter 4, p.94). The enhancement could be explained as being due to a role for bilateral symmetry per se or that the adjacent edges of contours from target and flanker provided additional shape information that was salient to detection via a process of a lateral interaction. In both experiments, the specific positions of the flankers with respect to the target was shown to be a factor in the level of facilitation. This is inconsistent with a role simply for a specific shared shape-level feature (e.g., bilateral symmetry), as in all cases, regardless of the position of the flankers, bilateral symmetry was always present at the individual shape level (target and flankers).

More specifically, the magnitude of the facilitation was greatest when the contours were aligned along the horizontal axis, while it was much reduced when aligned along the vertical axis. This orientation difference could have a number of explanations, the most plausible of which is that, at least along the horizontal axis there are novel, unknown lateral interactions that point to a role for inter-object contour symmetries (Koning & Wagemans, 2009; Baylis & Driver, 1995, 2001; van der Helm & Treder, 2009; Bertamini, 2010). in the perpetual organisation of a Gaborized contour. Hence, it is most plausible that the findings of the present experiments may demonstrate an inter-contour effect involved in perceptual grouping that is comparable to the effects of bilateral symmetry (Machilsen et al., 2009) on the detection of contours. However, it is not clear why these lateral interactions would result in inhibition along the vertical axis given that inter-object symmetries still arose in this condition.

The premise of investigating bilateral symmetry, or indeed inter-object symmetries, was that they represented potentially complementary feature-based perceptual processes that could influence the detectability of a contour in the target region. However, to a large degree the focus of research on these effects is ecological – both bilateral symmetries, and inter-object symmetries arise in highly specialised circumstances connected to biological and contextual factors. Accepting these kinds of motivations, one possibility is that flanker facilitation effects occurs due to common ecological factors that arise in groups of objects.

In the environment, for instance, animals, are less likely to be found directly above and below each other (with excepting circumstances such as goats, or for short durations, birds). Hence, it may be that the difference in the magnitude of the flanker facilitation may be environmentally tuned. In this sense, the differences observed in the findings are only circumstantially related to the presence of inter-contour symmetries. In other words, these observations may indicate a neurophysiological difference in how the visual system performs facilitation.

The methodology and stimuli employed in the experiment limited the overall scope of the interpretation of the findings in a two substantial ways. The methodology for testing the alignment was based on fixed distance between flankers and target. The distance between inter-object contours and when they interact in the integration process might depend on whether both fall in or outside receptive fields responsible for the relevant features. In order to investigate into the impact of alignment on target detectability, a more effective experimental layout could have been to use a circular concentric arrangement, in which a tuning curve for the flanker facilitation effect could have been extracted as a continuous function of angular distance and relative alignment from the centroid of the target.

One final, general point that concerns the use of contours is its relationship with the underlying generating shape that it represents. The retinal projection of the flanking contours in different locations with respect to the line of sight could have significant differences in the shape. This could, in part, explain the increase in facilitation with more flankers. Not every contour is contributing identical shape level information, hence, by increasing the number of flankers the visual system is more readily able to compensate for projective distortion. An implication of this idea is that the visual system may actively make use of differences between the shapes of the contours in a complex way that aids detection. Hence, the flanker facilitation effect may still occur if the flanking contour vary in absolute shape (e.g., curvature along the contours varies) with respect to the target contour.

5.7 Conclusion

This set of experiments has further characterised the flanker facilitation effect in a number of ways. In particular, the findings have shown that the perceptual mechanism is sensitive to scene level and contextual factors. The two factors tested, the numerosity of flanking contours and the alignment of the flankers with respect to the target contour, were both shown to modulate the magnitude of facilitation. This provides further support for the conclusion from a previous experiment – in which the flanker facilitation effect was associated with a probabilistic modulation of the contour integration process. However, it was not clear whether the asymptotic behaviour in facilitation based on increasing numerosity was associated with limitations of attention selection or represented a limit to the optimal amount of evidence required for the contour integration process.

Chapter 6

Shape similarity modulates the magnitude of the flanker facilitation effect.

6.1 Abstract

The visual system has been shown to systematically organize and group together local contrast features into a single coherent contour. This perceptual process, known as contour integration, is sensitive to both features in the contour (such as bilateral symmetry and shape familiarity) and the presence of flanking contours surrounding a central target contour. In particular, it has been shown that the presence of flanking contours facilitates the detectability of target contour when the shape of the flankers and target are the same. However, it is not clear whether the exact duplication of shape in both the target and flankers is necessary for the flanker facilitation effect. The present study investigated the role of shape similarity in the flanker facilitation effect; specifically, whether the flanker facilitation effect is a highly specialized process where the shape of the flankers and target must be the same, or a general facilitative process which is robust to changes in the common shape. Shape detection (contour integration) thresholds were measured using a 2-AFC adaptive staircase procedure in which orientation noise was added to the Gaborized contour until participants were unable to detect the target contour. Experiment 1 paired the target contour with flankers with (A) the same, (B) similar, or (C) dissimilar generating shapes to the target. The magnitude of the facilitation to the detectability of the target contour was greatest when the flankers were similar but not the same as the target contour. Experiment 2 examined conditions in which the shape of two flankers were either (A) matching or (B) non-matching. The magnitude of the flanker facilitation effect was the same for both matching and non-matching conditions. The findings indicated that the flanker facilitation effect was a generalized effect and is robust to both differences in shape between the target and flanker, as well as between the flankers. This study suggests an important role for common general shape among objects in the visual field on visual object processing (I.e., to aid in the detection of hard-to-discern object boundaries).

6.2 Introduction

To aid in the process of detecting objects in the visual field, the visual system makes use of the systematic regularities in the object, such as the presence of shape symmetry (Mach, 1885/1959; Attneave, 1954; Delius & Nowak, 1982; Bornstein et al., 1981; Wagemans, 1995; Treder et al., 2011; de Kuijer et al., 2004; van der Helm & Leeuwenberg, 1996, 2004; Friedenberg, 2000; Treder, 2010; Baylis & Driver, 2001; Machilsen et al., 2009); shape aspect-ratio (Zusne & Michels, 1962a, 1962b; Regan & Hamstra, 1992); contour convexity/concavity (Koffka, 1935; Kanizsa, 1976; Bertamini & Wagemans, 2013; Huttenlocher & Wayner, 1992; N. Rubin et al., 2000; Pao & Geiger, 2001) shape circularity/compactness (Zusne & Michels, 1962a, 1962b; Gallant et al., 1993, 1996; Wilkinson et al., 2000; Wilson & Wilkinson, 1998; Dumoulin & Hess, 2007); viewpoint ((Tarr & Pinker, 1989; Jolicoeur & Milliken, 1989; Moses et al., 1996; Vetter & Poggio, 1994; Palmer et al., 1981; Vetter & Poggio, 1994; Koenderink & Van doorn, 1979; Tarr & Kriegman, 2001); and how an object's parts relate to each other (Configuration) (Rensink et al., 1997; Bertamini & Farrant, 2005; Hoffman & Singh, 1997; Keane et al., 2003). However, these features are not simply passively detected; they play an active role in the organization of lower level information. For example, the detection of Gaborized contours is facilitated by a number of factors such as the presence of symmetries in the target contour (Machilsen et al., 2009), and the observer familiarity with a target contour (Sassi et al., 2014; Nygard et al., 2011; Sassi et al., 2012).

6.2.1 The role of context on object detection and perceptual organization.

Visual scenes with multiple objects can be quite complex in terms of spatial relations, and are affected by the viewpoint from which the observer sees the scene. Owing to both viewpoint and the relative positions of objects various forms of regularities can arise between objects. The visual system is sensitive to these regularities, such as inter-object symmetries (Koning & Wagemans, 2009; Baylis & Driver, 1995, 2001; van der Helm & Treder, 2009; Bertamini, 2010).; common shared features

(Stojanoski & Niemeier, 2007); the presence of additional redundant sensory cues (Todd, 1912; Miller, 1982; Krummenacher et al., 2001, 2002a, 2002b; Ben-David & Algom, 2009); and the average value of the features (e.g., size/orientation) of a set of objects presented simultaneously (Alvarez, 2011; Ariely, 2001; Chong & Treisman, 2003; Dakin & Watt, 1997; Chong & Treisman, 2003; Parkes et al., 2001; Alvarez & Oliva, 2008). The contextual sensitivity to multiple features and objects can aid in the perceptual organization of a hard-to-detect target. In particular, the presence of flanking contours has been shown to enhance the detectability of a target contour embedded in noise when the shape of the flankers is the same as the target contour (see Chapter 3, p.51).

This flanker facilitation effect has been shown to be a complex perceptual mechanism that is modulated by other factors such as the overall compactness of the inferred contour in the noise field (see Chapter 4, p.94), the number of flanking contours present, and the alignment of contours in the horizontal and vertical planes (see Chapter 5, p.131). These experiments presented flanking contours surrounding the target contour. The conditions consisted of comparing the detection thresholds of a Gaborized contour when it had the same or different shape as the target. However, the outline of, say, a cat can come in many similar but different shapes. The previous findings did not take into account the possibility that two shapes can be very similar, but substantially different local features. It is, for instance, known that the visual system does not encode every possible aspect of objects per se, but rather salient viewpoints that arise due to changes in the relative position of a viewer and an object (Tarr & Pinker, 1989; Jolicoeur & Milliken, 1989; Moses et al., 1996; Vetter & Poggio, 1994; Palmer et al., 1981; Vetter & Poggio, 1994; Koenderink & Van doorn, 1979; Tarr & Kriegman, 2001).

6.2.2 Experimental summary

The purpose of this study is to examine the robustness of the flanker facilitation effect to changes in the similarity of the shape between the target and flanker contours. To encode similarity, two target shapes were chosen and a set of flanking contour shapes was generated by interpolating between the target shape and one of two reference shapes with different degrees of shape compactness (a measure of the complexity of the shape perimeter). Previous experiments had demonstrated a role for compactness (see Chapter 4, p.94). For this reason, the two references were either low or high compactness (e.g., complex and simple shapes respectively). Sets of flanker shapes were generated that were increasingly dissimilar and more or less complex relative to the target. Here the compactness value is defined as the reciprocal of the complexity of a contour shape (1/complexity).

Contour detection performance across target-flanker conditions was compared to the control conditions where the target object was presented in isolation. Contour detectability was systematically degraded by the addition of orientation noise to the individual Gabor gratings making up the target contour. Detection thresholds were defined as the maximum amount of orientation noise that could be added to the contour before it became undetectable. Therefore higher levels of noise indicated more enhanced levels of detectability.

Two experiments were performed. The first experiment examined the effect of decreasing similarity of the flanker contours on the magnitude of the flanker facilitation effect. To do so, the target contour was paired with flanking contours that were either the same (target and flanking contours were the same shape), similar (the flanking contours were more similar to the target contours than the circle or cat reference shapes) or dissimilar (more similar to the circle and cat reference shapes). The second experiment compares the effects of two flankers with the same or different shape from each other. In other words, the left and right flanking contours were grouped according to whether they themselves were similar rather than due to the similarity of the flanking contours with the target contour.

6.3 Experiment 1

The purpose of the first experiment was to determine whether the flanker facilitation effect occurred only in circumstances in which the flanker and target contour were the same shape.

6.3.1 Methodology

Participants

15 participants performed the experiment. All 15 were paid undergraduate volunteers (£5 per hour). 10 of the participants were female. Their age range was 17 to 30. 14 of the participants had performed similar tasks in the previous set of experiments. Each participant performed one session (1 hour per session). Two breaks were provided during the session at approximately 1/3 and 2/3 of the way through the experiment and the duration was dependent on the participant. Each participant performed one session of 1 hour. All participants had normal or corrected-to-normal vision. Ethics was granted by the St Andrews University Teaching and Research Ethics Committee (UTREC- Ethics reference number: PS7638).

Apparatus

Experiments were presented on a Dell 2407WFP LCD display with a resolution of 1920x1200 with a refresh rate of 60Hz. The viewing distance was 57cm. Participants viewed the screen from a chin/head rest. The Experiment was implemented using Matlab (Mathworks, Inc) using the psychophysics toolbox utilities (Brainard, 1997). Statistics were performed in R (R Development Core Team, 2008) and presented using Gnuplot (Williams & Kelley, 2011).

Stimuli

The stimuli were created using the Grouping Elements Rendering Toolbox (Demeyer & Machilsen, 2012) based on Matlab programming language. The staircase procedure used to present the stimuli for each trial was run using the Palamedes Toolbox (Prins & Kingdom, 2001).

The stimuli consisted of two components: A set of sine waves windowed by a Gaussian envelope, known as a Gabor patch, and a generating shape combined with a set of Gabor patches to generate the stimuli presented to the observers.

The Gabor patches consisted of a sine wave luminance profile of frequency 2 cycles/deg and the 2-dimensional Gaussian envelope with a Gaussian standard deviation (sigma value) of 3 pixels. The phase of each Gabor patch was randomised by 90 degrees.

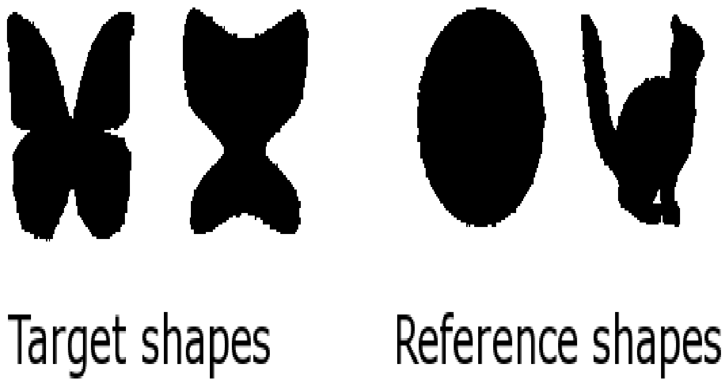

Figure 6.1: **Shapes used to generate target and flanker Gaborized contours.** Presented on the right are the shapes used as target contours, these were also used as flanking contours. Presented on the left are reference shapes used to generate intermediate shapes.

The flanker shapes were created by generating new shapes that were morphs between a target shape and a reference shape (see Figure 6.1). Each of the two target shapes were morphed to create the flankers, these had intermediate compactness values (greater and lower than the target shape) between the target and reference shapes. There were 2 levels of morphing between each target shape and each reference shape. The morphing procedure is described in appendix 4 (p.209).

This resulted in a total of 10 possible flanker shapes (2 the same as targets; 4 morphed shapes more complex than targets; 4 morphed shapes less compact than targets). Both the flankers and target shapes were then used to generate Gaborized contours using the same method as in previous experiments (see Chapters 3, 4 and 5, p.51, 94 and 131). These are shown in Figure 6.2.

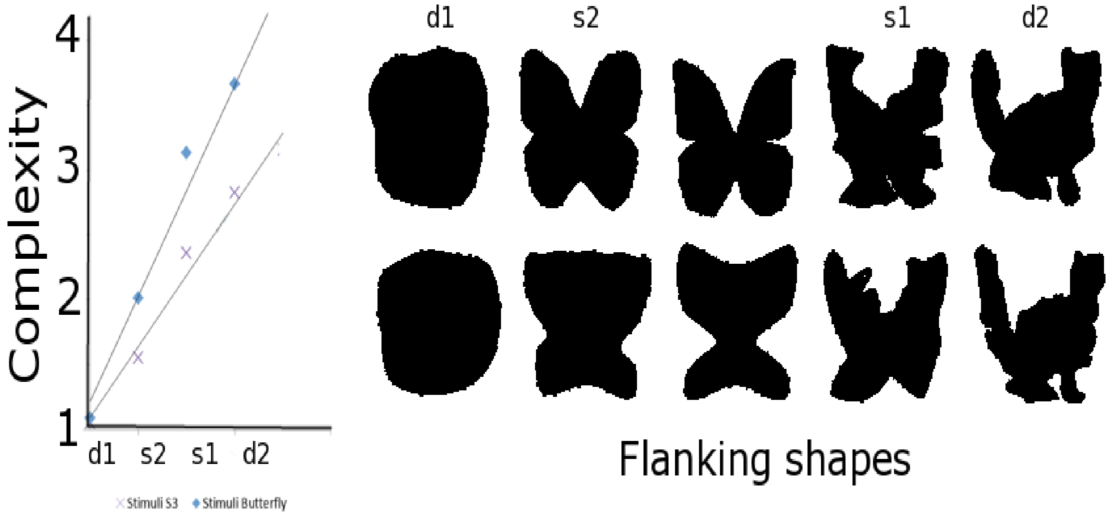

Figure 6.2: **Flanker shapes used to generate target and flanker Gaborized contours.**

The graph plots the compactness of the contour against the shape interpolated between the target and flanker shapes. The shapes are presented with decreasing compactness. These were 10 flanker contours that were the same (center), similar (s1/s2) and different (d1/d2) from the target contours.

Approximately 21 Gabor patches were placed along the perimeter of the generating shape (Figure 3.2) however minor adjustments (+/- 2 Gabor patches) were made by inspection if the resultant contour lacked corners or extrema. The orientation of these individual Gabor patches corresponded with the local orientation of the underlying generating shape. The width of these intervals was randomised. The maximum width to which subsequent Gabor patches could be positioned was a single wavelength.

The stimuli presented in the panels were presented on a grey rectangular panel (14x8 degree) which was placed on an otherwise black screen. The panel was primarily populated with a field of randomly positioned, non-overlapping, randomly oriented Gabor patches (referred to as the noise field). The average initial minimum spacing between Gabor patches in the noise field was around 16.5px. These Gaborized contours were then embedded in the noise field (see Figure 3.3 and 3.4) such that there was no overlap with randomly orientated noise Gabor patches.

The combination of the Gaborized contour and the noise field introduced possible variations in the density of the overall panel of Gabor gratings. To assess the presence of probabilistically significant density differences, and subsequently adjust the relative locations of the set of Gabor patches, a method native to the stimuli generating program, G.E.R.T, was used. This employed a Voroni tessellation to isolate the immediate area surrounding each Gabor patch and trace it as a polygon. The surface areas for the polygons were computed and compared across both the noise field and the embedded contours to determine that the surface areas were reasonably uniform across the whole stimuli.

The detectability of the target contour in a panel was varied by adding orientation noise jitter to the individual Gabors making up the contour (Figure 3.5). The amount of orientation noise jitter added across the set of Gabor patches was sampled from a normal distribution centered on a particular mean value (e.g., 50 degrees away from local contour tangent alignment). The maximum value such orientation jitter could take was the range of 90 to -90 degrees. In the set of experiment reported here and elsewhere, the dependent variable is reported as the magnitude of the orientation noise jitter.

For example, 40 degrees of noise jitter represented a highly visible contour with a low level of orientation noise jitter, while 120 degrees of noise jitter represented a contour with low visibility with a high level of orientation noise jitter. The effects of adding orientation noise to a smooth contour are presented in Figure 3.5.

Conditions were generated by presenting a target contour with two flankers whose shape could be either the same, similar or different to that of the target. A same condition consisted of flanker contours that had the exact same shape as the target contour.

A similarity condition consisted of flanker contours that were the 1st interpolated shape (s1/s2 - immediately adjacent to the target shapes in Figure 6.2) and those closest in compactness to the target contour. A different condition consisted of flanker contours that were the 2nd interpolated shape (d1/d2 - immediately adjacent to the reference shapes in Figure 6.2) and those least similar in compactness to the target contour.

Hence, in total there were 4 conditions: (A) control condition, (target contour presented alone) (B) same condition (target and flankers were same shapes) (C) similarity condition (target and flankers (s1/s2) were similar shapes) and (D) different condition (target and flankers (d1/d2) were different shapes).

The stimulus presentation consisted of either a target-present panel or a target-absent panel. In the target present panel the target was displayed in the centre of the panel. The flankers (when present) were displayed to the left and right of the target such that their centroid aligned with the target centroid, and where the horizontal distance between centroids was approximately 4.7 deg.

The target absent panel was identical to the target present panel except that there was no target contour present. In order to prevent any gross differences in perceived density of the two types of panels the average density of the target absent panels was generated by same to the value of the target present condition. The number of Gabor patches in the target-present and target-absent panels was therefore the same.

The resultant value was used to generate a second distracter panel that contained identical flanker-contours with no target-contour with the same Gabor grating density. This value was further used to create a set of 5 inter-trial display panels for each set of panels containing no contour information. The inter-trial displays contained randomly positioned and orientated Gabor patches only.

Procedure

The sequence of stimulus presentation (see Figure 6.3) involved an initial fixation cross at the center of the main display panel (800 ms), followed by a fixation cross appearing at the upper or lower half of the overall panel. This was followed by the presentation of either a target-present or target absent stimulus panel for 200 ms. After this time, a fixation cross appeared at the opposite location (lower or upper panel) and was followed by either the target-absent or target-present panel (depending on what was previously shown. A circle was presented with no fixed duration in which the participant was asked to respond if a contour was present in either the upper or lower panel. Once a response was recorded an inter-trial display was presented for 700ms and a central red circle was flashed up (200ms) to indicate the beginning of a new trial.

The initial presentation panel presented for each contour consisted of Gabor gratings aligned to the underlying generating shape. The initial level of noise jitter for each staircase was at 12 degrees of noise. That is, the contour was extremely visible and detectable to all participants.

The degree of orientation noise was varied according to participant responses using a weighted 1-up 1-down staircase procedure targeting approximately a detection threshold of 67 percent (Kaernbach, 1991). This rule was adopted after an initial 3 trials. The step size down in the initial 3 trials was 16 degrees of noise. This was intended on reducing the number of steps required before the target-contour became difficult to detect. If the participant was incorrect at the lowest level of noise the level of noise remained the same during the first three trials. After the first 3 trials 4

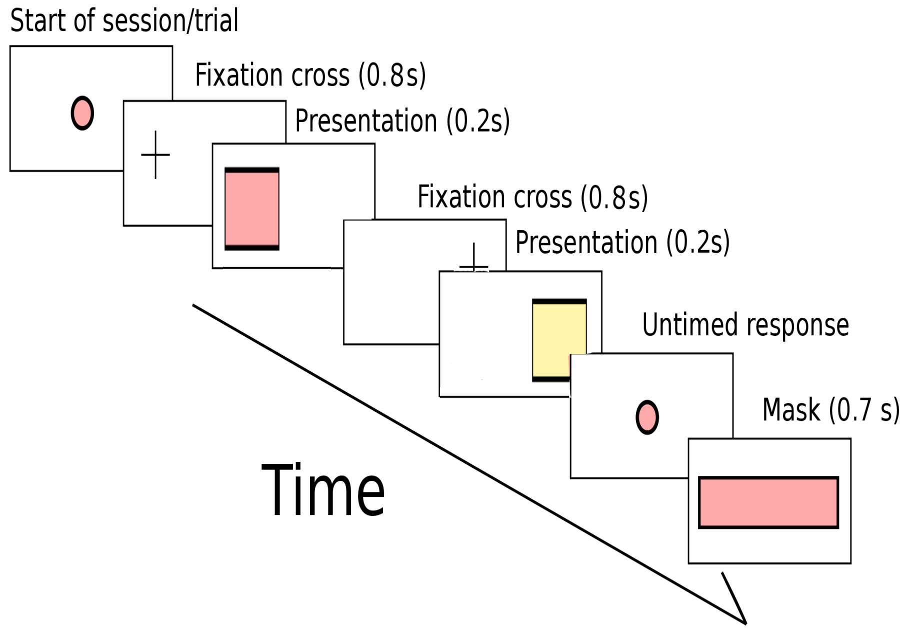

Figure 6.3: **The time course of a single trial**

The stimuli set consisted of two stimuli, either a target-absent or a target-present image one of which contained the target object and one without. Each presentation consisted of an initial fixation cross that directed the observer's attention to the target location, this was followed by one of the stimuli. The stimuli was presented on the right hand side (red) and then on the left hand side (yellow) on screen. Once the two stimuli were presented, a red circle appeared that prompted the subject to indicate in which stimulus (first or second) they saw a target object, this circle remained until the observer made a response. Finally, an inter-trial display was presented.

degrees of noise were added if the participant was correct and decreased by 4 degrees of noise if the participant was incorrect.

To extract the detection threshold using the staircase the degree of added noise at which the participant was no longer able to detect the shape was identified. Each staircase was terminated after 30 trials and the threshold was calculated by taking the mean value over which the 10 reversals took place. Here the detection thresholds are presented as the reciprocal detectability values, therefore a decrease in the detection threshold corresponds to an increase in the detectability of the shape under greater degrees of additional noise.

A number of participants could not perform the task for all contour types (that is, for complex contours such as the cat their performance was around the lowest level of additional noise). Additionally, a number of contours staircases over-shot the detection threshold and did not return in the allocated number of trials. Two limits corresponding to detectability values of 30 and 160 were chosen and data that was above or below these points was removed.

6.3.2 Results

In order to determine if there was an overall effect of the presence of flankers on contour detectability, the mean detection threshold for each stimulus condition (control, same, similar and different) was determined by averaging over all target contour shapes tested for each condition for each participant. The mean values averaging across all participant are shown in the bar plot in figure 6.4. The results indicate that the highest sensitivity (lowest detection thresholds) was obtained in the condition where the target contour was flanked by contours with a similar but different shape.

The observed increase in the detectability of the target contour is inconsistent with a simple increase in similarity between the target and flanker. While it was expected that the greatest facilitation should occur for the same condition, instead, the greatest facilitation occurred for the similarity condition, in which the flankers were similar but not identical in shape.

The difference in detectability between conditions was only near significance $F(3,42) = 2.56$, $p = 0.06$). However, the overall trend presented in Figure 6.4 appears consistent with a facilitating effect seen in previous experiments. This experiment tested less participants than the previous studies, therefore the results are likely to reflect the relative lack of statistical power.

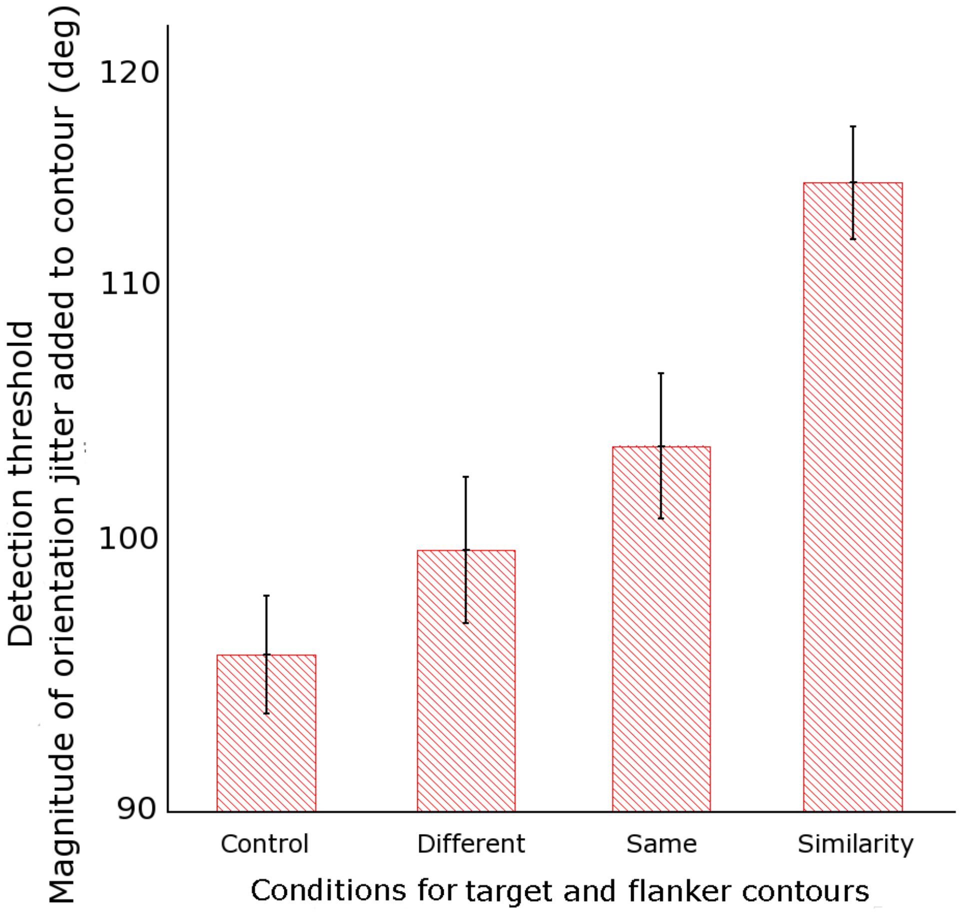

Figure 6.4: **The mean detection thresholds as a function of flanker similarity to target contour**

The detection thresholds thresholds are presented for each of the target-flanker conditions. The plotted conditions are the control condition (no flanker surrounding target); same condition (target and flanker share the same shape); similarity condition (target and flankers are similar shapes) and different condition (target and flanker have a different shape). The plotted data are the magnitude of orientation jitter added to a central target contour at a detection threshold of approximately 70 percent proportion correct averaged over all participants (n=10). Error bars represent the standard error of the mean.

6.4 Experiment 2

The first experiment involved the presentation of two flanking contours with the same or similar shape to the target contour. However, it is not clear whether the flanker facilitation effect is sensitive to differences in the similarity between the flanking contours themselves. Alternative combinations of flankers with shapes similar to the target but not matching each other could lead to the same magnitude of facilitation as combinations of flankers whose shapes are matched to each other. This was investigated by comparing the magnitude of the flanker facilitation effect when the flanking contours were the same as each other (matching condition) or different (non-matching condition) from each other.

6.4.1 Methodology

Participants

9 participants performed the experiment. All 9 were paid undergraduate volunteers (£5 per hour) who had performed the initial experiment. All 9 of the participants were female. Their age range was 17 to 30. Two breaks were provided during the session at approximately 1/3 and 2/3 of the way through the experiment and the duration was dependent on the participant. Each participant performed one session of 1 hour. All observers had normal or corrected-to-normal vision. Ethics was granted by the St Andrews University Teaching and Research Ethics Committee (UTREC).

Apparatus

The apparatus in Experiment 2 was identical with that in Experiment 1.

Stimuli

Three groups were created: (A) a control condition in which no flankers were present, (B) a matching condition in which flankers both had the same shape, and (C) a non-matching condition in which flankers were of different generating shapes. The flankers in the non-matching condition were paired to have two compactness values that, when combined, have an average complexity that was approximately the same as the actual compactness of the underlying target shape In comparison, the flanking contours in the matching condition had a range of different average complexity values.

Procedure

The procedure was identical to that in Experiment 1.

6.4.2 Results

In order to determine if there was an overall effect of the matching or non-matching conditions on the magnitude of the facilitation for a target contour, the mean detection threshold for each stimulus condition (control, matching and non-matching) was determined by averaging over all target contour shapes tested for each condition for each participant. The mean values averaging across all participant are shown in the bar plot in figure 6.5. The detectability of the target contour was higher in both conditions than that of the control. However, both matching and non-matching producing the same magnitude of facilitation. A one-way ANOVA was performed, with stimulus condition as the factor. The test indicated that there was a statistically significant difference in the detection thresholds $F(2, 16) = 11.94$, $p < 0.001$). Moreover, planned pairwise comparisons using a Tukey test revealed that the differences between the matching and control were significant ($p=0.05$), as were the differences between non-matching and control condition ($p = 0.01$).

6.5 General Discussion

The purpose of this study was to examine the importance of differences in contour shape between flankers and the target to the flanker facilitation effect by comparing the magnitude of the effect under a number of different conditions. More specifically, the experiments were designed to test whether the detectability of a target contour could still be enhanced despite the flankers having a decreasing similarity with the target contour. Two possible characterizations of the flanker facilitation effect were possible: (A) It occurs in specialized perceptual circumstances involving exact duplications of a shape or (B) it is a robust effect that occurs even when multiple similar but different shapes are present in the visual field.

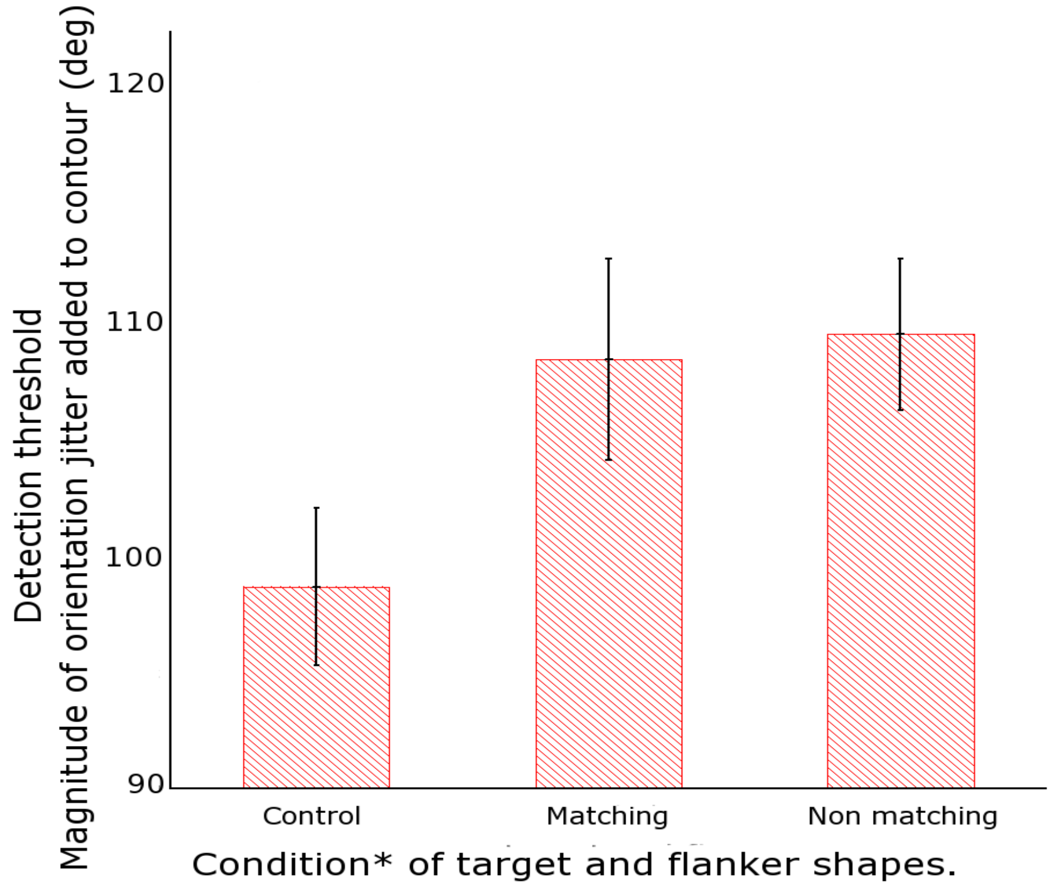

Figure 6.5: **The mean detection thresholds as a function of matching or non matching flanker shape**

The detection thresholds are presented for each of the target-flanker conditions. The plotted conditions are the control condition (no flanker surrounding target); matching condition (both flankers share the same shape); and non-matching condition (flankers are different shapes). The plotted data are the magnitude of orientation jitter added to a central target contour at a detection threshold of approximately 70 percent proportion correct averaged over all participants (n=9). Error bars represent the standard error of the mean.

Experiment 1 compared the effects of horizontally positioned flankers with same, similar or different generated shapes on the detectability of the target contour. The results indicated that the greatest degree of facilitation occurred in the presence of flankers with similar shapes as the target. This was inconsistent with the expected outcome as it indicated that there was an advantage in having slight differences in shape between the flankers and target.

Experiment 2 compared the effects of matching condition with those of non-matching condition and examined how differences between flankers modulated the shape level facilitation process. Both conditions produced the same magnitude of facilitation in comparison with the control.

These findings demonstrated that the flanker facilitation effect was a general perceptual effect that could occur when there were differences between the shapes of the flanker and target contours (Experiment 1). In turn, as the magnitude of the flanker facilitation effect was similar in conditions where both flankers had either the same or similar shapes (Experiment 2) it suggests that the visual system is sensitive to general shape of the flanker, rather than a direct template matching procedure or one involving lateral interactions between exact matches of lower level features of the contours (e.g., correlating subsections of curvature or extrema).

Previous experiments have found that the flanker facilitation effect is dependent on the compactness (contour complexity) of the common shape as well as the numerosity of shapes present (see Chapter 4, p.94). It was also proposed that correspondences in curvature between the adjacent edges of the closed contours could account for an enhancement observed when the flanker contours were adjacent along the horizontal condition. However, in both experiment 1 and experiment 2 of the current study there were differences in the curvature between the adjacent edges of contours in both the similarity and different flanks conditions. Despite this, the flanker facilitation effect showed comparable magnitudes of facilitation.

While these experiments do not rule out the possibility that the adjacent edges are enhancing the detection process it suggests that the differences in the magnitude of the flanker facilitation effect between alignment above/below and left/right of the target contour (see Chapter 5, p.131) may not be due to additional lateral interactions (due to inter-object symmetries), but rather may reflect some intrinsic neurophysiological constraints on the flanker facilitation effect. In turn, the lack of corresponding curvature across the edges of contours suggests that the visual system is indeed sampling shape level information from the flanking contours to perform detection. While previous research linked the compactness to the flanker facilitation effect it is possible that the two factors that are used to formulate compactness, that is, the contour length and the area that it enclosed, are important to the flanker facilitation effect and are combined separately.

Alternatively, compactness may indeed be the salient psychophysical property. One possibility is that the compactness is being encoded as a mean property of items in the region including and surrounding the target, as has been shown for other visual properties (Alvarez, 2011; Ariely, 2001; Chong & Treisman, 2003; Dakin & Watt, 1997; Chong & Treisman, 2003; Parkes et al., 2001; Alvarez & Oliva, 2008). Hence, the mean compactness value might be extracted from the flankers and the distributive properties of this value might be utilized in some probabilistic way for determining the most likely smooth contour in the target region.

The flanking contours in the non-matching condition (Experiment 2) were paired in so that the mean complexity (1/compactness) of both flankers was the same as that of the target. This was not true of the matching condition, in which the various pairs of flankers had mean compactness values that differed from the target contour. It therefore seems unlikely that it is a mean complexity per se that is important to the visual system. However, the visual system could be using a similar holistic measurement to compactness rather than extracting the 2nd order properties (e.g., area and contour length). For instance, researchers have in the past identified a technique that can capture the convexity of the overall shape (Pao & Geiger, 2001). The model for such a global convexity measurement is very similar in form to compactness with a key difference being that it captures changes in the types of curvature integrated across the whole contour.

There were a number of idiosyncrasies in the dataset that are problematic for any further interpretation. For instance, in experiment 1 the greatest magnitude for the facilitation effect was observed in the similarity rather than same condition. This was unexpected as the changes to the overall shape should reduce the shape level information available to the visual system. There were several possible reasons why this may have occurred.

The visual system may have become more sensitive to local information when a large number of otherwise similar features were presented simultaneously. Such effects have been shown to occur in the detection of differences in large similar patterns (Mundy et al., 2007, 2009). Hence, the enhancement in the similarity condition compared with the same condition may be attributable to an enhancement to decision making processes that are designed to detect differences between samples.

In other words, when the flanking contours were similar but not same flank to the target contour they may have activated a number of other processes that were related to the enhanced detection of differences. In the similarity condition then, the visual system had simultaneous access to the overall shape level similarities, as well as the localized differences between the two, with the combination of both providing a larger evidence base, or activity level, resulting in superior detection. However, while this may account for the enhancement, it may be that the effects of orientation noise on the shape of the detected contour (see Chapter 4) induce an overall shape that has a greater similarity to the flankers in the similar condition when compared with the same condition. That is, the orientation noise reduces the similarity between the target and flanker in the same condition, while increasing the similarity between the target and flanker in the similarity condition.

An important fact to note is in that in previous experiments (see Chapter 5) there was an enhancement to the magnitude of the flanker facilitation effect that was associated with the alignment of contours introducing inter-contour symmetries. However, in conditions involving flanking contours that differed in shape from the target, the adjacent edges of the target and flankers had different curvature from each other. Despite this, the magnitude of the flanker facilitation effect was greatest when the flankers were of a similar shape; hence, it is likely that this previous finding may represent an underlying spatial response of the perceptual mechanism responsible for the flanker facilitation effect rather than a direct, lateral interaction between adjacent contour sub-regions of reflected curvature.

Finally, as the stimulus set used a small number of shapes it is possible that these findings are specific to the contours used in the experiment. Hence, the findings will need to be validated using a more extensive set of contours.

6.6 Conclusion.

Overall, these findings demonstrated that the flanker facilitation effect does not require the curvature information between contours in the visual field to be the same. In other words, the effect is a general effect that is tolerant to differences in shape. This implies that the flanker facilitation effect is sampling shape information relating to the holistic shape (factors such as compactness, aspect-ratio, general area, etc.) rather that encoding precise mid-level psychophysical factors (such as convexity of contour curvature, inter-object symmetries).

The flanker facilitation effect represents a perceptual mechanism in which the grouping of local orientation occurs more readily when there are flanking contours present. However, there are a number of other changes in local information that could benefit from this type of mechanism (such as the relative positions of the Gabor patches). Further research may demonstrate whether the flanker facilitation effect modulates the local orientations or is a family of effects that influences other types of localized features.

Chapter 7

Conclusion

7.1 Overview of thesis

In looking at an object and its reflection in a mirror, the visual system is confronted with two views of a single object that coexist simultaneously. Such scenarios are not uncommon in the environment with similar visual information from different points of the visual field occurring, for example, when an observer sees a group of animals, tree-lines at the horizon, or a scientific illustration showing a sequence of change in cell growth.

Perceiving a single object is in itself not a simple process and requires the visual system to parse and segment the localised areas of contrast and bind them together into a full object. However, environmental situations, such as a bright light, complex arrangements of parts (e.g., hundreds of leaves from a single branch) or other obscuring objects (e.g., an animal lying in grass) can lead to difficulties in how easily different parts of the visual field can be segmented and/or grouped together.

Changing viewpoints and the presence of other similar objects in the visual field can present large amounts of salient spatial and identity information. This additional visual information could be useful to the visual system for resolving the ambiguities that arise from objects that are difficult to segment from the overall scene.

A number of perceptual enhancements arise when multiple objects and features are presented simultaneously (see General Introduction, Chapter 1, p.6) however, it is not clear to what degree this contextual and perceptual information could influence the perceptual organisation of an object. The central premise of the thesis was: How does the visual system use visual information from objects across the visual field in order to visually process an object in the central field of view?

The initial, exploratory motivation for this thesis was to determine if there was an effect of flanking object shape on the detectability of a central target shape. As with any exploratory investigation there are two important goals. Firstly, to reconfirm any novel observations under a number of criteria. Secondly, to characterise the findings in such a way as to create a provisional descriptive model which could be used in the future to explore the phenomenon further.

The thesis consisted of three distinct parts: The initial development of a strategy to investigate the effects of shape level information on low level details (Chapter 2 and 3, p.30 and 51); replicating the pattern of results under more comprehensive experimental conditions to establish the validity of the previous findings (Chapter 4, p.94); and characterising the identified perceptual mechanism (Chapter 5 and 6, p.131 and 160).

The overall set of reported experiments discovered a specific and novel shape level flanker facilitation effect. This involved an increase in the detectability of Gaborized target contours when they were presented in conjunction with flankers of the same underlying generating shape. This perceptual mechanism was shown to be sensitive to a number of scene level factors including the number of flankers present; contextual factors such as relative position and inter contour alignment; the inherent complexity of the contour shape and the degree of shape similarity between the target and flanker contours.

7.2 Summaries of experimental findings.

7.2.1 Chapter 2 – Is the detectability of a 3-D object embedded in multi-scale noise affected by the presence of neighbouring objects? (Pilot experiment)

The purpose of Chapter 2 (p.30) was to develop and test a methodology to investigate whether the shared shape of a target and flanking object affected the detectability of the central target. This initial pilot experiment made use of 3-dimensional objects and embedded them in multi-scale noise. The purpose of this was to disrupt a number of low level features equally while preserving the visibility of the overall shape configuration of the parts of the target object.

A 2-AFC experiment was designed in which the detectability of the target object was varied by modifying the opacity of the noise. This involved modifying the relative contributions of the target object and the multi-scale noise to the final pixel value of the stimuli presented. The contribution of the multi-scale noise was increased until the target object was no longer visible to the participant. The detectability of the target objects was compared under a number of conditions that paired the object with flanking objects with either similar or dissimilar configurations or shapes.

Participants reported difficulties with performing the task and subsequent analysis identified a number of issues associated with the use of multi-scale noise that required further testing. For this reason the overall stimuli and strategy were revised and the dimensionality of the target stimulus was reduced (2-D vs. 3-D shapes) while a specific perceptual process (contour integration) was chosen for further investigation.

7.2.2 Chapter 3 – Is the detectability of a Gaborized contour modulated by the presence of nearby flanking contours?

In light of the pilot experiment, Chapter 3 (p.51) examined a stimuli set of a lower dimensionality (2-D Gaborized contours). The experiments focused on whether the presence of flanking contours with similar or dissimilar shape as the target contour facilitated the target's detectability.

The general motivation for this was to isolate the stimuli to study a specific perceptual process, contour integration, rather than the larger range of complementary processes involved in detecting a 3-D object. The stimuli consisted of Gaborized contours embedded in a Gabor noise field. The Gaborized target was presented with and without flankers. Four conditions were tested in which the target contour was presented by itself with flankers that matching the shape of the target (same condition) and two conditions in which the shape of the target and flankers were different shapes, but were either the same shape (different matching condition) or different shapes (different non-matching condition).

By determining the detectability of the target contours (2-AFC procedure with orientation jitter as the dependent measurement) it was demonstrated that the presence of flankers with the same generating shape as the target contours facilitated the mean detectability of the target contours. However, a number of potential confounding factors were identified which included the differences in perimeter complexity of the target-shapes, the presence of symmetry, and the recognisability of the generating shapes. These factors potentially contributed to variations in the magnitude of the flanker facilitation effect.

7.2.3 Chapter 4 – Contour integration is facilitated by the presence of adjacent contours that share shape-level features.

The motivation of Chapter 4 (p.94) was to replicate the findings of the previous chapter using a large number of new generating shapes. These contours were constrained by taking into account a number of additional factors such as the presence of symmetry, shape familiarity and the complexity of the shape. The purpose of this chapter was to strengthen the findings of the previous experiments by investigating whether the magnitude of the facilitation effect was due to random noise or due to systematic contributions from specific factors.

The methodology employed was similar to the previous chapter with an adjustment to the adaptive staircase procedure to reduce the difficulty of the procedure for the participants. This involved increasing the detection threshold from 50 percent to 67 percent correct. Four groups of 5 contours each were generated based on the presence or absence of two shape level features: bilateral symmetry and shape familiarity. A measurement of the complexity of the contours in terms of shape compactness (Zusne & Michels, 1962a, 1962b) was used to ensure that a range of shapes of varying shape complexity was tested.

Three conditions were tested in which the target contour was: presented by itself (control condition); presented with flankers that were the same as the shape of the target (same condition); flankers that were not the same shape as the target (different condition). The presence of flankers with the same generating shape as the target contours facilitated the mean detection thresholds of the target contours. However, the magnitude of the flanker facilitation effect was enhanced in the presence of bilateral symmetry.

To take into account the complexity of the target contour, a new measure, the compactness differential was used to compare the effect of orientation jitter on the complexity of the target contour independently of the underlying complexity of the shape used to generate the target. The importance of this measurement was that it was based on the assumption that the visual system was detecting a smooth contour (that followed the orientation of the local Gabor patches) in the target region.

The detection performance in terms of compactness differentials were compared with the underlying shape complexity. The detection performance for all contours across both the control and same conditions was systematically related to shape complexity in comparison to the original measure used (orientation noise magnitude). This suggested that the visual system was performing smooth contour extraction from the noise field and detecting the most likely closed contour given the available orientation of the local features, and other additional information (e.g., shared features with flanking contours).

7.2.4 Chapter 5 – The magnitude of the flanker facilitation effect on contour integration is modulated by changes in spatial location and numerosity of flanking contours.

The results of Chapter 4 indicated that there were two factors that influenced the magnitude of the flanker facilitation effect: the underlying complexity of the shapes used for contours and the presence of bilateral symmetry in the contours. In particular, the enhancement associated with bilateral symmetry was confounded by the presence of inter-object symmetry cues that occurred due to the spatial alignment of the target and flanking contours.

To investigate how the flanking contours played a role in the flanker facilitation Chapter 5 (p.131) studied the role of the numerosity and alignment of the flankers with respect to the target contour. Using a subset of previously examined contours, the detectability of the target contours in the presence of flankers was compared by varying two factors: numerosity (increasing the number of flanking contours around the target contour) and alignment (changing the relative position of the flanking contours with respect to the target contour).

The first experiment investigated the increase in the number of flanking contours from 0 to 4 flanking contours. In the first part of the experiment, the flankers were presented arranged in one of four locations – above, below, right and left of the target contour. In the second part, the flankers were presented in positions that was diagonal to the target contour (e.g., the upper or lower corners of the presentation). There was an increase in the magnitude of the facilitation with some evidence of the increase asymptoting at higher numerosity.

To determine whether there was a greater enhancement for the target contour when it was aligned with the flankers, the positions of the flankers were presented either aligned, or misaligned in two different ways with respect to the target contour.

These were tested for either a horizontal or vertical arrangement of flanker contours. Alignment was observed to play a role in the magnitude of the flanker facilitation effect. More specifically, there were differences in the magnitude of the effect depending on whether the flankers were presented above/below and left/right of the target contour. No facilitation was observed when the flanking contours were above and below the target. In turn, there was greater facilitation when flankers were positioned left and right of the target contour in comparison with other spatial arrangements.

Overall, these findings indicated a number of important factors involved in the flanker facilitation effect. The flanker facilitation effect was sensitive to the numerosity of the flankers. In addition, the fact that the greatest facilitation was observed for horizontal alignment, suggests that the enhancement observed in previous experiments was plausibly connected to a lateral interaction between the adjacent edges of the target and flanking contours.

7.2.5 Chapter 6 – Shape similarity modulates the magnitude of the flanker facilitation effect.

The previous experiments had determined that (A) a flanker facilitation effect occurred when target contours were presented with flankers with the same shape (B) that this process appeared to be related to the extraction of a smooth contour (C) that contextual factors such as numerosity and position of flankers modulated the magnitude of the flanker facilitation effect. The purpose of this set of experiments was to investigate whether the magnitude of the effect was robust to changes in the degree of similarity of the flanking and target contours. The main implication of robustness is that it determines whether the flanker facilitation effect is a specific effect or a generalised effect (occurs despite varying degrees of difference in the shape of the objects present in the visual field).

To determine the nature of the perceptual process, a new set of contours was generated taking into account both the similarity and the compactness of the shapes (see Chapter 6, p.160). These shapes were generated with respect to two reference shapes of high and low compactness. Conditions were created by pairing the target contour with flankers that had different degrees of similarity to the shape of the target contour. In the first experiment the target contour was paired with sets of two horizontally located flankers that had the same, similar, or dissimilar generating shapes with respect to the target contour. The second experiment examined the magnitude of the flanker facilitation effect when the flankers themselves were either in the matching or non-matching conditions. That is, the shape of both of the flanking contours was either the same, or different from each other.

The findings indicated that the magnitude of the flanker facilitation effect was greatest when the flankers were in the similarity condition. As the flanker facilitation effect occurred despite a lack of direct correspondence of local information between the target and flankers, or between the flankers, these findings suggest that the visual system was extracting a general shape information from the flanking contours. In addition to this, as the similarity or non-matching condition did not contain inter-object symmetries and the flanker facilitation effect in the former was either greater or the same as in those conditions that did have inter-object symmetries, it demonstrated that it was not a lateral interaction between adjacent regions of the contours that was responsible for enhancements seen in Chapter 4. As the similarity or non-matching condition did not contain inter-object symmetries but the flanker facilitation effect was either greater or the same as in those conditions that did have inter-object symmetries it demonstrated that it was not lateral interactions between adjacent regions of the contours that was responsible for enhancements seen in Chapter 4.

7.3 The flanker facilitation effect – Summary of findings.

The detection of a single object in the environment can be readily described by identifying how sensitive the visual system is to certain features (e.g., symmetry), and how this sensitivity varies when the complexity of the target varies (e.g., the addition of orientation noise along the edge of a target contour). However, as this thesis studied the interactions between two or more discrete contours, it is necessary to take three mutual factors into account to characterise the flanker facilitation effect: the detection of the target, the sampling of flanker information, and the integration of the sampled information into the target detection process.

The conclusion is therefore thematically organised:

(A) How does the detection of a target contour take place in the presence of flanking contours?

(B) What is the role of the flanking contours and how does the visual system sample information from the flanking contours?

(C) Are there any additional long range interactions that may indicate that the flanker facilitation effect involves either a single perceptual mechanism or multiple mechanisms?

7.3.1 How is the detection of a contour effected by the presence of flanking contours?

The detection of a Gaborized contour involves the successful grouping of local features into a closed contour. A standard method of investigating this process of contour integration, and the one used in this thesis, is to embed a contour into a larger set of distracter Gabor patches and introduce orientation jitter (I.e., decrease the alignment of the individual Gabor patches along the perimeter of a contour) until a participant is unable to distinguish one randomised Gabor region with the target contour from one without a target (2-AFC procedure). By determining this detection threshold, and comparing the detectability of target contours with and without flanking contours with the same/different shape from the target it was possible to investigate the influence of additional shape level factors across the visual field on the integrative process.

Chapter 3 (p.51) determined that the detectability of Gaborized contours was greater for target contours with adjacent flankers of the same shape. In turn, by surrounding the flanking contours with isolinear Gabor fields (I.e., to increase the visibility of the flankers) it was shown that the facilitation effect could be observed across a range of shapes of varying complexity. A number of potentially important factors were identified during the experiments. Firstly, that there may have been a contribution to the detectability (either facilitatory or suppressive) related to the familiarity of the contour used and the type of Gabor field across the visual field (isolinear vs. random orientation). Secondly, that the complexity of the shape influenced the likelihood that the facilitation was observed. Finally, that there may be a role of feature−based attention, with an enhancement in the magnitude of the effect due to a shared symmetry between the target and flanking contours.

To distinguish between these factors and to determine if there was a real facilitatory effect associated with the presence of flankers per se Chapter 4 (p.94) incorporated two new aspects: A larger set of new shapes was grouped by general familiarity (I.e., the contours were of everyday objects) and the presence of symmetry (more specifically, bilateral symmetry). In addition to this, the complexity of the contours was used to quantify the orientation jitter in terms of the effect of orientation change on the whole contour shape. This measurement, the compactness differential, reinterpreted the orientation jitter at the detection threshold for the individual contours so as to take into account the change to complexity of the whole contour during the experiment.

The findings of Chapter 4 (p.94) indicated that the detection performance (with or without the presence of flankers) was indeed systematically captured by taking into account the compactness differential and the underlying complexity of the whole shape of the target contour. This demonstrated a key finding: the perceptual mechanism that underpinned the flanker facilitation effect appears to involve the detection of the most likely smooth contour in the target region, rather than matching the region to some pre-existing template. A second finding of this chapter was that the presence of symmetry enhanced the magnitude of this effect. However, this explanation could not be fully accepted as symmetry in the contours would also introduce inter-object symmetries, which may have produced some kind of target enhancing lateral interaction. As well as this, it may have been due to an implicit association between symmetry and simpler contours.

Based on these findings, the flanker facilitation effect appears to involve the incorporation of sampled shape level information from the surrounding flankers which provide additional information to the attended target region, which in turn permits the detection of harder to detect smooth contours within the noise field. In other words, it is not the detection of a specific contour that is facilitated, but rather, the detection of the most likely contour given the local orientations present.

7.3.2 What is the role of the flanking contours and how does the visual system sample information from the flanking contours?

The initial experiments of Chapter 5 (p.131) sought to investigate the importance of increasing numerosity of flanking contours to examine how the visual system sampled from the region surrounding the target. In order to take into account the possible lateral interactions due to inter-object alignment, the role of flanker numerosity was investigated in two ways – directly adjacent (above/below/left/right) or diagonal to the target contour.

The magnitude of the flanker facilitation effect was shown to increase with flanker numerosity and asymptote when approximately 4 contours were present. This asymptotic trend could be explained in two ways: either the visual system requires a small sample of shapes to achieve optimality, or, that the limitations on attention prevent any more sampling of information from the flankers. Chapter 5 investigated this sampling process further by studying whether the shapes used as either target or flankers had to have the same local features (say, curvature) within them, or, whether the flanker facilitation effect was robust to differences in the shape of the contours. Neither the correspondence of target-flanker shape, nor flanker-flanker shape was required for the flanker facilitation effect to occur. More specifically, the detectability of the target contour was greatest when the flanking contours were similar but not the same shape as the target contour.

This finding strongly suggested that the process of sampling from the flanking contours was using general psychophysical factors or holistic shape-level information from flanking contours to modulate local contour integration, rather than a simple template match, or shape priming. As Chapter 4 (p.94) had established a link with the compactness (1/complexity) of a contour and its detectability, it was therefore possible to argue that it was this factor or one related to it (e.g., aspect-ratio, global convexity) that was being sampled from the flanking contours. However, as Chapter 4 demonstrated, there was also a potential role for the presence of symmetry.

The key findings were therefore that the visual system is sampling holistic shape information from the flanking contours and that the magnitude of this effect increased with the number of flankers present surrounding the target contour. This weakened considerably the idea that the facilitation effect may occur due to flankers being treated as a template or a shape prime.

7.3.3 Is the flanker facilitation effect a single perceptual mechanism?

Chapter 4 (p.94) demonstrated that there was an enhancement to the magnitude of the flanker facilitation effect when the contours contained a symmetry. However, this effect could have been due to either the symmetric target and flankers corresponding to simpler, easier to detect shapes, or, alternatively, that there was an important role for symmetry that increased the magnitude of the flanker facilitation effect. It was therefore possible that this enhancement was linked to a second novel facilitatory effect in which the presence of bilateral symmetry increased the visibility of the unattended flankers in a way consistent with a study in which feature-based attention modulated peripheral flankers (Stojanoski & Niemeier, 2007). However, the presence of symmetry introduced other inter-object contour symmetries and these may have been the cause for the enhancement (Koning & Wagemans, 2009; Baylis & Driver, 1995, 2001; van der Helm & Treder, 2009; Bertamini, 2010).

Chapter 5 (p.131) investigated this by studying the effects of the number of contours by changing the alignment of the flanking contours by using either a vertical or horizontal arrangement of flanker and target contours. It was found that the greatest magnitude of the flanker facilitation occurred when the flankers were left/right of the target contour. No facilitation occurred when the flankers were above/below the target contour, while intermediate magnitudes of facilitation occurred in the other locations surrounding the visual field.

This was a complex finding for two reasons: as the magnitude of the facilitation was greatest when the flanking contours were left/right of the target contour it seemed to imply that it was lateral inter-object rather than feature-based interactions that were responsible for the previous enhanced detectability. However, this could not explain why there was no facilitation when the flankers were presented above/below the target contour. So, while these findings suggested that the enhancement in this instance was connected with inter-object effects it was difficult to interpret, on these grounds why there would be no facilitation when the flankers were presented above/below the target contours.

Chapter 6 (p.160) determined that the magnitude of the facilitation was greatest for contours that were similar but not the same as the target contour. The implication of this was that in this condition there was little to no exact correspondence in the curvature between the adjacent edges of the contours. Hence, it is likely that the results of Chapter 5 were not due to lateral interactions between adjacent edges of the contours per se, but rather they represent a spatial dependence in the flanker facilitation effect. In this case, the perceptual mechanism responsible for the flanker facilitation effect, based on the results in Chapter 5, may indicate that information is more easily sampled from flankers placed in certain spatial locations with respect to the attended target contour.

The key findings of these chapters are that the observed enhancement in Chapter 4, due to the presence of symmetry, is most likely due to the perceptual mechanism responsible for the flanker facilitation effect being more responsive to simpler rather than symmetric contours. In addition, the facilitation effect has an as-yet unaccounted spatial dependence which modulates how strong the flanker facilitation effect is.

7.3.4 The flanker facilitation effect and low level processing

In the realm of local processing, both suppressive and facilitatory effects on the activation of a target region by the presence of stimulation in a surrounding region have been observed to occur in early visual system, e.g., surround suppression, crowding, and the local flanker facilitation effect. Surround suppression, for instance, involves the reduction of target detection sensitivity or discrimination of a target feature (e.g. relative orientation) due to the presence of another similar stimulus element nearby. More specifically, such lateral suppression or inhibition appears to be feature specific, e.g., orientation or colour. (Tadin et al., 2003; Born, 2000; Pack et al., 2005; Churan et al., 2009; Spillmann, 1994; Troncoso et al., 2007; Petrov et al., 2007; Polat & Sagi, 1993; Adini et al., 1997; Zenger & Sagi, 1996; Bonneh & Sagi, 1999; Churan et al., 2009; Cass & Spehar, 2005; Chen & Tyler, 2001; Freeman et al., 2001; Huang & Hess, 2007; Mizobe et al., 2001; Katkov & Sagi, 2010; Polat & Tyler, 1999; Sterkin et al., 2008; Woods et al., 2002; Bouma, 1970; Stuart & Burian, 1962; Pelli & Tillman, 2008; Toet & Levi, 1992; Levi, 2008; Levi et al., 2002; Parkes et al., 2001; Pelli et al., 2004)

Superficially then, one could compare the flanker facilitation effect observed in this thesis with such processes. However, one reason to believe that this effect is not identical to such processes, and might involve feedback processes occurring globally at a higher level of processing, rather than simple lateral interactions, is that the effect identified here appears to integrate or propagate information from a higher level feature (e.g., shape compactness) into local processing (contour integration of Gabor elements). This leads to an interesting central question: What is happening to these local mechanisms during the flanker facilitation effect? For instance, would the presence of two flankers surrounding a target contour effect a participant detecting the orientation of a single Gabor patch within the target contour?

7.3.5 The flanker facilitation effect and the redundancy signal effect

A second aspect of the flanker facilitation effect, unexamined in the course of this thesis, is the importance of the time taken for the local and global processing to occur. One temporal mechanism that may be relevant is the redundant signals effect (RSE). In this perceptual process, two or more signals (e.g., a tone and a light) from different modalities presented together enable better rate of detection for one of the signals (e.g., the light) than if they were presented alone. For example, the reaction time to the presentation of a briefly presented spot of light is faster if it is accompanied by the presentation of a simultaneous brief tone, than if the light spot is presented by itself (Todd, 1912; Miller, 1982; Toellner et al., 2011; Krummenacher et al., 2001, 2002a, 2002b; Ivanov & Werner, 2009; Grubert et al., 2011).

In comparison to the RSE, the flanker facilitation effect involves the influence of shape information relating to objects surrounding a target object, whose local information was disrupted by orientation noise. In the experiments conducted, this process of detection was given a fixed time period. One possibility is that the flanker facilitation occurs, in part, because the flankers facilitate the temporal integration process required to detect the target. In other words, the simultaneous presentation of globally relatable contours decreases the processing latency for certain global features, such as contour closure or shape recognition. Further research examining the time course of the flanker facilitation process would illuminate the connections between these two perceptual phenomena.

7.4 Further directions

The discovery of a general enhancement in the detectability of a target contour due to the presence of additional flankers within the visual field has a range of implications both within the context of the psychophysical factors that underpin it as well as the experimental evidence in other areas of object detection and recognition.

The importance of more global and cognitive factors to local grouping has been investigated by a range of studies that have established that the contour integration process is sensitive to a variety of different factors such as symmetry, familiarity and the predictability of the target contour presented (Sassi et al., 2012; Machilsen et al., 2009; Sassi, Vancleef, Machilsen, Panis, & Wagemans, 2010; Sassi et al., 2014; Nygard et al., 2011). Alongside this, the present thesis has identified another factor that influences these localised processes – whole shape information presented in surrounding flanking contours.

The numerosity of flankers and their influence on detecting a separate target contours has a global importance – it demonstrates that the closure of a contour is best not thought of as a simple product of perceptual processes that are centered on a specific region of the visual field (Pettet, 1999; Kovacs & Julesz, 1993) but rather the resultant percept, the closed contour, is a product of a complex and holistic response to objects across the visual field. In this context, the flanker facilitation effect has an interesting potential: as it allows the determination of what psychophysical factors actively modulate the closure process, it forms another investigative link to study both the bottom-up and feed-back processes within the visual system involved in contour integration.

Although the use of contour integration is premised on the local grouping of Gabor patches it can also be considered as a form of Figure-ground segmentation, in which the Gaborized contour is the figure contained within a background consisting of a noise field. A number of illusions involve the bistable reversal of a figure with the background (face-vase illusion). If the above experiments are involved in resolving the differences between figure and background, the temporal behaviour of bi−stability may be affected by the presence of flanker contours with specific information. More simply, if the face-vase is presented with flankers with the shape of a vase it may be expected that the temporal duration of the observation of the lamp shape may occur for longer.

In terms of the perceptual mechanism that underpins the flanker facilitation effect there are a large number of generic psychophysical factors that could be tested (e.g., aspect-ratio; convexity; frequency of Gabor patches; peripheral distance of flankers and contours; and flankers organised in more complex configurations than equidistant contours on both sides) and fields (e.g., direct contour integration, figure-ground segmentation, influence with redundancy effects) that need to be investigated before we truly understand why and how the visual system has developed this ability.

7.5 Conclusion

To the author's knowledge, this is the first demonstration that the contour integration and subsequent detection of a Gaborized contour is modulated by the presence and shape of surrounding flanking contours. As a perceptual mechanism, the flanker facilitation effect was shown to be sensitive to general shape level information which was used to determine the most likely smooth contour within an otherwise randomised group of Gabor patches. This process was shown to be robust to differences in otherwise similar shapes. This general mechanism may be important for understanding how the visual system resolves other types of shape ambiguities within the visual environment and, in turn, may be used to further investigate how the visual system performs the perceptual organisation of a scene.

Chapter 8

Appendix 1

8.1 Pov-ray object stimuli

8.1.1 Purpose

The stimulus used in the initial pilot experiment (Chapter 2, p.30) consisted of 3-D objects obscured by multi-scale noise. The detectability of the target objects was measured as a function of the opacity of the noise with respect to the object. This was tested under conditions in which the target object was paired with and without additional flanking objects. These had a number of similarities and differences in visual information along two factors: the configuration of the parts of the objects and the overall shape. These object stimuli were generated by Pov-ray

8.1.2 General description

Pov-ray can generate pictorially realistic geometric objects and pattens with changes in luminance (e.g., number of light sources, how diffuse or direct the lighting effects are) and object-luminance interactions (e.g., projective shadows, lighting changes due to roughness). To render realistic objects, the program uses a procedure known as 'ray-tracing'. The intuition that governs this method is that the pattern of luminance projected onto the retina can be used reconstruct the path of the light-rays if one knows the position of the observer with respect to an initial light source.

8.1.3 Methodology

The methodology consists of three procedural element: (A) the 'camera view' from which the program calculates each pixel for the resultant image (B) A hypothetical light source from which light rays traced from the camera view is traced to, and (C) an object-primitive, which is defined as a set of coordinates located with respect to the camera and light source.

More specifically, from the coordinates of the camera view, a set of vectors are generated that link the viewpoint to the coordinates of the object-primitive. The corresponding points are then used and a further set of vectors are generated that link the object-primitive to the hypothetical light source. The luminance for each pixel is determined by inspecting the vectors that pass from the camera view, via the object-primitive to the hypothetical light source. Shadows are defined by the subset of vectors that intersect the volume defined by the object-primitive before they arrive at the light source.

The benefits of using a procedure such as ray-tracing is that it reduces the overall computational difficulties associated with rendering all possible projected light-rays from a light source. By restricting the calculation to the projected shape and the subsequent vector for the coordinates to a single point the resultant vectors can be used to define gradients and shadows in the hypothetical luminance.

Chapter 9

Appendix 2

9.1 Multi-scale noise

9.1.1 Purpose

The detectability of the initial pilot experiment (Chapter 2, p.30) was investigated by adjusting the pixel value of a target object with respect to a randomised pattern of luminance. The factors tested was object level information such as (A) the overall shape, and (B) the configuration of the parts of the whole object.

However, 3-D objects contain a large number of types of features (e.g., curvature of object boundaries, diffuse gradients of luminance) that have varying sizes and scales relative to the whole object. A multi-scale noise was generated using the standard Perlin procedure (Perlin, 1983) to create a set of pixel values with noise both at a local pixel level, as well as scales comparable to the length of edges and areas of the parts of an object. This noise was generated using a dedicated noise generation library for C++.

9.1.2 General description

The multi-scale noise is described as coherent noise, this contrasts with standard white/pink/brown noise which is known as incoherent noise. Incoherent noise is a set of discrete points whose resultant pixel values are independent from each other.

That is, each pixel can take any value, and the whole set of values is defined by a maximal and minimal possible values only. (e.g., any pixel value can be between 0 to 255). Coherent noise involves a subset of randomised pixels at regular intervals. The values for pixels between the intermediate values are interpolated from the adjacent pixel values.

As coherent noise is defined by a set of regular intervals at which a randomised value is generated they can be characterised as frequency harmonics with an associated amplitude corresponding to the absolute range of the possible values (I.e., coherent noise is has sine-like properties such as wavelength, frequency, amplitude and phase). By combining a large number of such frequencies noise is introduced at both a level corresponding to pixel level regularities, but also on shape-level feature such as symmetry and curvature.

9.1.3 Methodology

To interpolate the noise value: (A) a grid of 4 points was defined at which the pixel value was randomised, with the interpolated value lying in the middle of the grid. The value of the gradient of the central point with each of the individual values at each of the 4 coordinates was calculated. Using a weighting function based on an s-shaped curve the individual interpolated values were combined. The frequency of the coherent noise was defined by the spatial interval at which the randomised noise was generated (e.g., the width of the grid used to interpolate the intermediate pixel values of noise)

The multi-scale noise combines a large number of these coherent noise waves. This led to a number of constraints on the multi-scale noise, firstly, the number of different frequency harmonics that were present, and secondly, the relative differences in amplitude for each frequency component. Frequency harmonics were combined in regular sets of octaves.

Each subsequent frequency component was defined as the nth power of 2. The initial frequency was adjustable by changing the initial value, 2, to a higher value. To determine the amplitude of each frequency harmonic with respect to each subsequent noise wave a value, known as the persistence was chosen. The amplitude for each frequency harmonic was decided as the nth power of the persistence. These relationships are shown in the Figure below.

The resultant multi-scale noise image appeared as a natural texture that resembled cloud-like patterns. The use of this noise enabled a disruption of features on the spatial scales of each frequency of coherent noise generated. Multi-scale noise has a number of advantages, the most significant of which is that it allows a preservation of features that are lower than the lowest frequency harmonic present with features of higher spatial frequencies disrupted across such scales to differing degrees.

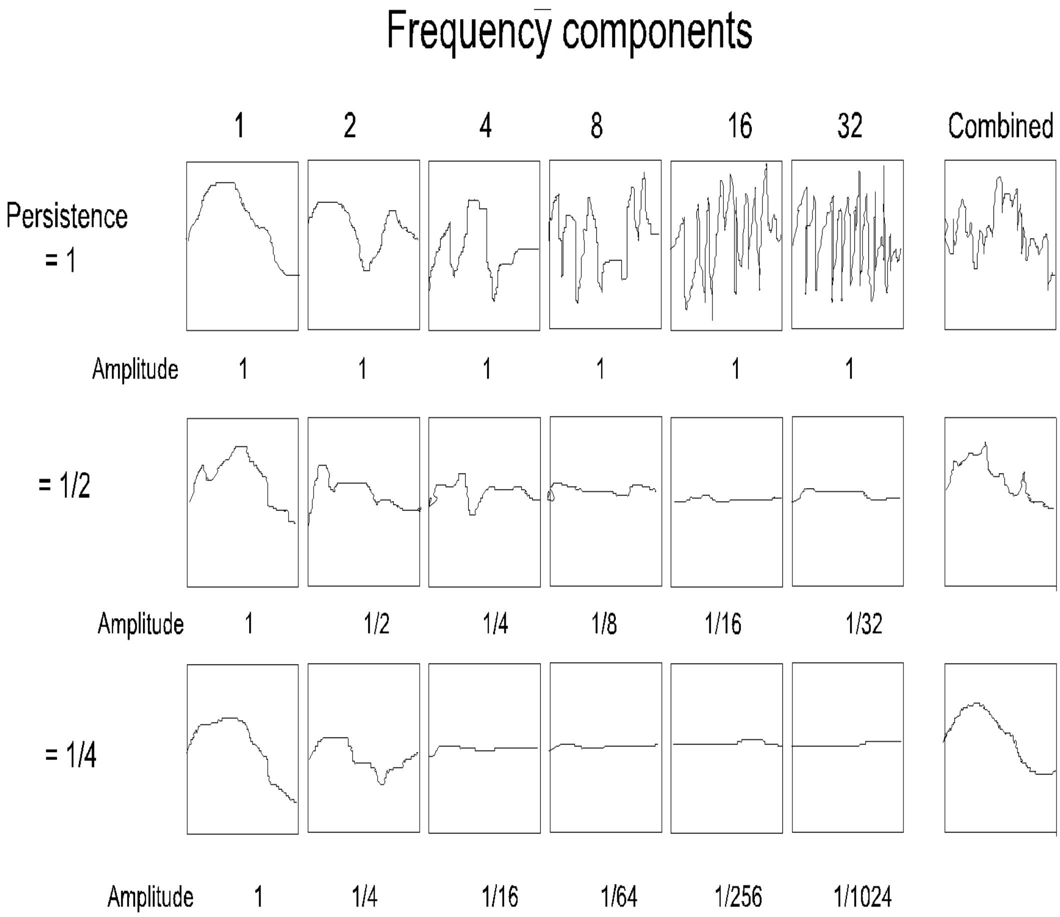

Figure 9.1: **Coherent and incoherent noise waves**

The harmonic frequencies and resultant multi-scale noise are shown above. Each inset square corresponds to a single frequency component. The amplitude of each frequency is determined by an initial persistence value. Each harmonic is combined and results in the combined multi-scale noise on the left hand side.

Chapter 10

Appendix 3

10.1 Measurement of change in compactness.

10.1.1 Purpose

The Gaborized contours used in the experiment consisted of a group of profiles of both everyday and geometric shapes. However, the contours contained a large amount of changes in contour and overall distribution across a given area. Plausibly, the complexity of the processing of the flanking contours played a role in how efficiently the flanker facilitation effect may take place.

In other words, the visual system may have found more complex contours more difficult to integrate into a contour and was less able to extract shape level information. To determine the potential role of complexity and whether the performance was related to this factor, compactness was used to assess the difficulty that the visual system had in integrating the central target (Chapter 4, p.94).

10.1.2 General description

The introduction of orientation noise jitter along the Gaborized contour changed the overall complexity of the target contour being detected. One method of considering this change is to assume that the visual system is extracting a smooth contour regardless of the introduction of orientation noise. Hence, the addition of orientation noise corresponds with a decrease in the compactness of the target contour.

Given a certain initial compactness an estimate was devised that determined the contribution of orientation noise to the change to compactness. That is, the added complexity due to modifying the orientations of the Gabor patches. This was performed manually in a vector based graphics program Inkscape.

One issue with this approach is that randomly introducing changes in orientation in this way introduces non-linear changes in the contour length. To overcome this, an estimation was made of the change to compactness of 1 deg of orientation noise.

The estimation was used to convert the detection thresholds into a corresponding measurement of the compactness at the point of detection. The initial compactness of the contour was then subtracted from this to determine the complexity added to the target contour before detection failed.

10.1.3 Methodology

The initial contours used a vector representation which traced out the initial shape. To determine the compactness, a native application in Inkscape was used to make measurements of the length of the shapes contour and the area that it enclosed. Two reference Gaborized shapes were chosen − a Circle and a Butterfly.

Splines for a vector shape were manually matching to the reference shapes. Correspondingly, a set of 3 Gaborized versions of these shapes (That is, the version that were be shown during each trial) at 5 different levels of orientation jitter (50, 70, 90, 110 degrees of orientation jitter) were placed under the vector shapes.

The individual splines of the vector shape were aligned to the Gabor patches under increasing degrees of noise. This produced a vector shape that corresponded with a smooth shape given the local values of the orientated Gabor patches.

This new contour length and area was measured for the shapes with larger amounts of orientation noise. The average change to the contour length for 1 degree of noise was calculated. This number was used to convert the detection thresholds into absolute values concerning the overall change to the compactness for the increase in orientation noise jitter.

Chapter 11

Appendix 4

11.1 Interpolation of intermediate shape contours.

11.1.1 Purpose

The contours in the chapters 3 to 5 (p.51 to 131) were generated from groups of unique shapes. However, an infinite range of changes in curvature and area can lead to large numbers otherwise similar shapes. To investigate the effects of increasing dissimilarity a number of contours were generated that were based on an initial target contour (Chapter 6, p.160).

11.1.2 General description

To constrain the possible range of changes to shape the overall shape was morphed into a more and less complex shape (e.g., Circle and Cat). Furthermore, this morphing procedure was used in conjunction with compactness. Any changes were chosen such that the resultant compactness was an approximately linear change.

11.1.3 Methodology

Two sets of shapes were chosen: (A) target shapes and (B) reference shapes. An interpolation was performed between the target and reference shapes in Inkscape, this process adjusted the individual splines along the shape. However, the interpolation introduced rotations along the splines that created loops in the contour length. These were manually adjusted and removed from the vector shape. The shapes were measured for compactness and were rejected if the compactness was non-linearly related to the target contour.

Chapter 12

Appendix 4

12.1 Ethical approval

University of St Andrews

University Teaching and Research Ethics Committee

13 June 2011

Ethics Reference No: *Please quote this ref on all correspondence*	PS7638
Project Title:	Similarities between objects – how do shared visual features affect the ability to detect an object hidden in visual noise?
Researchers Name:	Christopher Gillespie
Supervisor:	Dr Dhanraj Vishwanath

Thank you for submitting your application which was considered at the Psychology School Ethics Committee meeting on the 8th June 2011. The following documents were reviewed:

1. Ethical Application Form 08/06/2011
2. Participant Information Sheet 08/06/2011
3. Consent Form 13/06/2011
4. Debriefing Form 08/06/2011

The University Teaching and Research Ethics Committee (UTREC) approves this study from an ethical point of view. Please note that where approval is given by a School Ethics Committee that committee is part of UTREC and is delegated to act for UTREC.

Approval is given for three years. Projects, which have not commenced within two years of original approval, must be re-submitted to your School Ethics Committee.

You must inform your School Ethics Committee when the research has been completed. If you are unable to complete your research within the 3 three year validation period, you will be required to write to your School Ethics Committee and to UTREC (where approval was given by UTREC) to request an extension or you will need to re-apply.

Any serious adverse events or significant change which occurs in connection with this study and/or which may alter its ethical consideration, must be reported immediately to the School Ethics Committee, and an Ethical Amendment Form submitted where appropriate.

Approval is given on the understanding that the 'Guidelines for Ethical Research Practice' (http://www.st-andrews.ac.uk/media/UTRECguidelines%20Feb%2008.pdf) are adhered to.

Yours sincerely

Convenor of the School Ethics Committee

Ccs Dr Dhanraj Vishwanath (Supervisor)
School Ethics Committee

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